Executive Summary: Marine and Estuarine Shoreline Modification Issues

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As part of the process outlined in Washington's *Statewide Strategy to Recover Salmon: Extinction is Not an Option* the Washington Departments of Fish and Wildlife, Ecology, and Transportation were charged to develop Aquatic Habitat Guidelines employing an integrated approach to marine, freshwater, and riparian habitat protection and restoration. Guidelines will be issued, as funding allows, in a series of manuals addressing many aspects of aquatic and riparian habitat protection and restoration.

This document is one of a series of white papers developed to provide a legitimate scientific and technical basis for developing Aquatic Habitat Guidelines. The white papers address the current understanding of impacts of development and land management activities on aquatic habitat, and potential mitigation for these impacts. Individual white papers will not necessarily result in a corresponding guidance document. Instead, guidance document development, addressing management and technical assistance needs, may incorporate information synthesized from one or more of the white papers.

The scope of work for each white paper requested a “comprehensive but not exhaustive” review of the peer-reviewed scientific literature, symposia literature, and technical (gray) literature, with an emphasis on the peer-reviewed literature. The reader of this report can therefore expect a broad review of the literature, which is current through late 2000. Several of the white papers also contain similar elements including the following sections: overview of the guidelines project, overview of the subject white paper, assessment of the state of knowledge, summary of existing guidance, recommendations for future guidance documents, glossary of technical terms, and bibliography.

This white paper addresses the impact of marine and estuarine shoreline modifications on naturally functioning fish and shellfish habitat in Washington State.

"Nearshore" marine habitats within Washington State span a continuum from upland to subtidal areas, and are defined to encompass the zone wherein direct functional interactions (e.g., sediment supply, primary production and export) occur between upland and marine habitats. Marine shorelines in Washington state can be grouped into three distinct regions: the shores of the inland coastal waters of Puget Sound and the Strait of Juan de Fuca; the outer coast fronting the Pacific Ocean; and the shores of outer coast estuaries. Within these regions, estuarine and nearshore marine habitats can take many forms, including eelgrass (especially *Zostera marina*) meadows, kelp forests, sand and mudflats, tidal marshes, river mouths and deltas, sand spits, beach and backshore areas, banks and bluffs, and marine riparian areas. Broadscale patterns in Washington state's saltwater shoreline habitats have recently (1995-2000) been characterized under the Washington Department of Natural Resources ShoreZone mapping system that characterizes important physical, biotic, and anthropogenic features that can be considered indicators of ecosystem health. However, longterm monitoring databases and historic inventories are generally inadequate to assess and evaluate most nearshore habitat and resource trends in Washington State.

Human shoreline modifications in the region are commonly designed and built to dissipate wave energy, maintain navigation channels, control shoreline erosion, repair storm damage, protect from flooding, store or accumulate sediment, and promote commercial or recreational activity. General descriptions of these structures are as follows: 1) breakwaters and jetties that project into subtidal areas and are designed to dissipate wave energy, protect backshore areas, and direct tidal flow; 2) shoreline armoring or stabilization methods that include bulkheads, revetments, seawalls, groins, ramps, beach nourishment, and biotechnical approaches; and 3) tide gates, sewer outfalls, and artificial reefs that provide for a variety of other human needs (e.g., farmland creation, runoff and waste conveyance, and fishing and diving opportunities). Nearshore and estuarine resources of Washington State have been severely impacted by these shoreline modifications, which are particularly prevalent in the most populated areas of Washington State. Over 29% of Puget Sound's shoreline are stabilized by structures, with 1.7 miles of Puget Sound shoreline being newly armored each year. In King County alone, recent surveys have shown that armoring comprises 75-87% of the coastline.

Washington State's nearshore ecosystem plays a critical role in support of a wide variety of biological resources, many of which are commercially, culturally, aesthetically, and recreationally important to the people of the region. Nearshore habitats perform a variety of important functions within the ecosystem and support the life history and ecology of many species. For example, the nearshore foodweb is based upon detritus produced by plants (marine algae, estuarine and saltmarsh vascular plants, and especially eelgrass) that grow in highly productive shallow water habitats. Furthermore, shallow estuarine and nearshore habitats are structurally complex (e.g., submerged aquatic vegetation and large woody debris) and dynamic. As such, they are nursery areas for juvenile salmonids and other highly visible species (e.g., forage fishes, rockfishes, birds, and invertebrates) because they provide food, refuge from predators, spawning habitats, and a transition zone to physiologically adapt to salt water existence. All juvenile salmon move along the shallows of estuaries and nearshore areas during their outmigration to the sea, and may be found in these habitats throughout the year depending on species, stock, and life history stage.

Two complementary approaches are usually combined to interpret the ecological impacts of structural shoreline modification to the functionality of estuarine and nearshore marine habitats: 1) a conceptual approach involving inferences based on an informed understanding of the ecosystem and its processes, and 2) a direct approach that documents cause-and-effect through biological study. In general, most of our current understanding is based on a conceptual approach because relatively little controlled research has been directed at documenting and understanding the functional impacts of shoreline modifications to biological resources. Few studies have applied rigorous, hypothesis-based testing that confirms these impacts.

The conceptual approach assumes that shoreline modifications will exert effects at varying degrees on an ecosystem's controlling factors. Controlling factors are physical processes or environmental conditions that control local habitat structure and composition (e.g., vegetation, and substrate), including where habitat occurs and how much is present. In turn, habitat structure is linked to support processes, such as shading or cover, which are linked to ecological functions. Thus, impacts that affect controlling factors within an ecosystem will be reflected in changes to habitat structure, and will ultimately be manifested as changes to functions supported by the habitat. The effect at the functional level depends upon the level of disturbance and the relative sensitivity of the habitat to the disturbance. While far more work is needed to quantify the fundamental relationships between habitat conditions and controlling factors for the nearshore environment in Washington State, a preponderance of inferential evidence exists to link the effects of shoreline modifications to changes in nearshore biological functions.

Besides simplifying shorelines and reducing intertidal habitat area, shoreline modifications have direct effects on nearshore processes and the ecology of nearshore dependent species by reducing the area of shallow water habitat and its functional attributes. The primary mechanism of these effects is manifested through chronic changes in regional hydrology (e.g., altered wave energy and current patterns, obstruction of littoral drift and longshore sediment transport, and altered fluctuations of temperature, salinity, and water levels), as well as direct impacts on structural aspects of the site (e.g., permanent change of habitat, reflective turbulence, turbidity). In turn, shoreline modifications may impede the movement of species; alter substrate characteristics; change primary production, food web dynamics, and predator-prey interactions; and modify residence patterns that affect nursery or physiological transition functions. The design and location of shoreline structures can significantly affect relative impacts to nearshore biological resources. Furthermore, effects appear to be highly site, habitat, and scale-dependent, and depend upon the level of disturbance and the relative sensitivity of the habitat to the disturbance; it is difficult to accurately generalize a finding from one site to another site. While the adverse environmental impacts associated with a single shoreline stabilization structure may not always be great, there is a growing concern regarding the cumulative ecological effects of shoreline armoring within a landscape. From a landscape perspective, the cumulative impact of losses in connectivity between natural nearshore and estuarine habitats remains difficult to measure and untested.

A broad array of habitat protection and mitigation techniques exist that can minimize or limit the impact of shoreline modifications to estuarine and nearshore marine areas. Actions that can mitigate these impacts include avoidance (i.e., no shoreline modification), minimization of impacts by using alternative structural modification strategies (e.g., "soft" approaches that involve natural materials that can deform and adjust over time to changing shoreline conditions), land use management (e.g., building setbacks, storm and groundwater management, and vegetation management), and compensation via restoration of other degraded sites. There is a need to systematically examine the long-term success or relative benefits these approaches accrue as habitat to nearshore species. Properly designed estuarine restoration projects, including shoreline structure removal, may return a habitat to a close approximation of its condition prior to disturbance. However, restoration actions vary widely in their "success" rate. The potential for success varies depending on the degree of disturbance that exists at the site and within the landscape where the restoration site is located. Measures for protecting and restoring critical shoreline and estuarine habitats should incorporate principles of landscape connectivity and extend to activities outside of their conveniently defined boundaries.

While our review of the available research literature shows that explicit documentation is limited, adequate evidence exists to suggest that shoreline modifications have a high potential for severely impacting nearshore biological resources in Washington State. The following recommendations are offered as part of a comprehensive strategy to better protect, restore, and enhance associated nearshore and estuarine habitats in the region:

- A thorough physical assessment on a site-specific basis must be carried out to fully understand and document the potential direct, indirect and cumulative impacts prior to allowance of any shoreline modifications
- Protect and restore sensitive marine nearshore and estuarine habitat and ecological functions by avoiding shoreline structural modifications altogether.
- Where new shoreline modifications must occur, impacts should be minimized by pursuing alternative techniques (e.g., beach nourishment) and placement strategies
- Phased restoration of natural processes and ecological functions should be achieved through the strategic removal of unnecessary shoreline structures, especially in areas with particularly high rates of shoreline armoring and habitat structural modification.
- Restoration projects are uncertain and must be planned and evaluated carefully.
- Existing documents (Dethier et al. 1990, Simenstad et al. 1991a) should be used to provide a solid scientific basis for assessing the potential effects of changes caused by shoreline modifications and restoration on habitats and resources.
- Existing baseline inventories (e.g., WDNR 2000, ShoreZone Inventory database) should be used for determining habitat trends, locating critical areas for protection or restoration, and identifying nearshore ecosystems most at risk to cumulative impacts.
- A comprehensive research program is needed immediately to provide critical empirical data required to understand the relationships between placement of artificial structures in the marine environment and direct, indirect, and cumulative physical and biological changes that will occur on a local and larger scale.

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Overview of Aquatic Habitat Guidelines Project

As part of the process outlined in Washington's *Statewide Strategy to Recover Salmon: Extinction is Not an Option* the Washington Departments of Fish and Wildlife, Ecology, and Transportation were charged to develop Aquatic Habitat Guidelines employing an integrated approach to marine, freshwater, and riparian habitat protection and restoration. Guidelines will be issued, as funding allows, in a series of manuals addressing many aspects of aquatic and riparian habitat protection and restoration.

This document is one of a series of white papers developed to provide a scientific and technical basis for developing Aquatic Habitat Guidelines. The white papers address the current understanding of impacts of development and land management activities on aquatic habitat, and potential mitigation for these impacts. The following topics are addressed in the white paper series:

- Over-water structures - marine
- Over-water structures - freshwater
- Over-water structures - treated wood issues
- Water crossings
- Channel design
- Marine and estuarine shoreline modification issues
- Ecological issues in floodplain and riparian corridors
- Dredging - marine
- Dredging and gravel removal - freshwater

Individual white papers will not necessarily result in a corresponding guidance document. Instead, guidance documents, addressing management and technical assistance, may incorporate information from one or more of the white papers. Opportunities to participate in guidelines development through scoping, workshops, and reviewing draft guidance materials will be available to all interested parties.

Principal investigators were selected for specific white paper topics based on their acknowledged expertise. The scope of work for their projects requested a "comprehensive but not exhaustive" review of the peer-reviewed literature, symposia literature, and technical (gray) literature, with an emphasis on the peer-reviewed literature. Readers of this report can therefore expect a broad review of the literature, which is current through late 2000. The coverage will vary among papers depending on research conducted on the subject and reported in the scientific and technical literature. Analysis of project specific monitoring, mitigation studies, and similar efforts are beyond the scope of this program.

Each white paper includes some or all of these elements: overview of the Aquatic Habitat Guidelines program, overview of the subject white paper, assessment of the state of the knowledge, summary of existing guidance, recommendations for future guidelines, glossary of technical terms, and bibliography.

The overarching goal of the Aquatic Habitat Guidelines program is to protect and promote fully functioning fish and wildlife habitat through comprehensive and effective management of activities affecting Washington's aquatic and riparian ecosystems. These aquatic and riparian habitats include, but are not limited to rearing, spawning, refuge, feeding, and migration habitat elements for fish and wildlife.

Introduction

The research and information in this paper, addressing marine and estuarine shoreline modification issues, is based on comprehensive but not necessarily exhaustive reviews of the pertinent peer-reviewed papers, symposia proceedings, agency documentation, engineering works, and other relevant information known to the authors. The topics addressed in this marine and estuarine shoreline modification issues white paper include structural and non-structural shoreline stabilization methods (e.g., bulkheads, beach nourishment, biotechnology, setbacks, vegetation management, ground/surface water management), tide gates, outfalls, artificial reefs, and estuary restoration.

This report summarizes the state of current knowledge and technology pertaining to marine and estuarine shoreline modification issues and provides liberal in-text citations of the source materials. In general, primary sources have been sought out and preferred to secondary sources, and a fully detailed bibliography of sources cited as well as an appendix of consulted literature and other sources of information is provided. The methods used in conducting the literature review are described in the methods section of the paper.

This white paper provides an overview of marine and estuarine shoreline modification issues associated with construction and restoration activities, structures, and features. The ecological and habitat issues associated with these structures, features and activities, as well as mitigation techniques for ecosystem impacts are addressed. Recommendations for future guidelines documents have been included, based upon issues, conclusions, and data gaps identified in this research effort. The report is addressed to a generalist audience, and the use of technical jargon has been avoided. A glossary of specialist terminology is provided as an appendix.

Assessment of the State of Knowledge

Methods

Literature searches were conducted at the University of Washington School of Fisheries and Oceanography library. Search techniques included the use of the Cambridge Scientific Abstracts (CSA) service to search key databases: Aquatic Sciences and Fisheries Abstracts (ASFA, 1978-current), National Technology and Information Service (NTIS; 1964-current), Oceanic Abstracts (1981-current), Pollution Abstracts (1981-current), Toxicology Abstracts (1981-current), and Water Resources Abstracts (1967-current). Keyword searches were determined by white paper guidelines and author searches by frequency in relevant subject areas. Additionally, we used an extensive company library of gray literature sources, supplemented by discussions with experts in the field. Our compilation of literature sources focused on nearshore structures in coastal marine and estuarine habitats, but we also included relevant citations on freshwater systems, and general ecological studies that examined fish behavior. This literature includes peer-reviewed journal articles, theses/dissertations, technical reports, and books; unpublished research was addressed through personal communications with active researchers.

Our discussion of the literature centers on the direct and indirect biological effects of shoreline modification activities, especially as they affect salmonid, other finfish, and shellfish populations, and is supplemented by a review of mitigation and restoration options and benefits. It will be used to update Shoreline Management Guidelines, and will be passed on to local governments to use while they update their shoreline management protocols. Because of inherent overlap between the impacts of shoreline and overwater structures, this white paper (Williams and Thom, in review) focuses on shoreline impacts that affect hydrology, whereas that of Nightengale and Simenstad (On- and Overwater Structures White Paper, in review) concentrates on overwater impacts that affect light attenuation and shading.

This white paper begins with an overview of ecological and habitat issues related to estuaries and nearshore marine areas. This overview defines key terms, describes and reviews pertinent habitat functions, and defines the scope of shoreline modifications and restoration. The paper continues with a summary of fish and shellfish use patterns in estuarine and marine nearshore habitat, focusing on the functional benefits these habitats provide. A conceptual model is then introduced that provides a framework with examples for understanding ecological responses of organisms to habitat modification. Effects of various shoreline modifications are reviewed, addressing, in turn, relevant construction and operation techniques, actual studies that have documented direct biological impacts, and probable biological impacts based on documented physical changes. Habitat protection and mitigation techniques are then reviewed, including natural alternatives to shoreline modification and restoration approaches. We conclude with a list of existing guidance materials related to shoreline modification practices, summary conclusions from a synthesis of our findings, recommendations for additional guidance and research needs, and a proposed strategy for implementing these actions.

Overview of Ecological and Habitat Issues

Definition of Estuarine and Nearshore Marine Habitats

"Nearshore" marine habitats within Washington State can be variously defined and span a continuum from upland to subtidal areas. For the purposes of this paper, "nearshore" habitats are defined to encompass the zone wherein direct functional interactions (e.g., sediment supply, primary production and export) occur between upland and marine habitats. Thus, the marine nearshore zone includes those areas between the lower limit of the benthic photic zone (the depth where light can no longer sustain plants, including microalgae). This lower depth range is variable and depends on water clarity. Healthy benthic vegetation can be found down to depths of about -10 to -30 m relative to Mean Lower Low Water (MLLW = 0 m) in Puget Sound. It is within this depth at least where there is a strong coupling between benthic processes (e.g., nutrient cycling) and the entire overlaying water column. For example, we have observed evidence of nearshore-offshore coupling through organic matter transport wherein primary production in shallow nearshore habitats moves to deeper regions of Puget Sound via currents and gravity.

The upper limit of the nearshore zone includes that area landward some distance from the intertidal zone. The strongest intertidal-upland coupling occurs where bluffs provide sediments that nourish beaches, where upland transition (e.g., dune) vegetation stabilizes the beach, and where fringing vegetation shades the intertidal zone and contributes insects (i.e., fish prey) and leaf litter (i.e., primary production) directly into the aquatic environment. This marine riparian zone also provides buffers from upland noise and water runoff. The characteristics and landward extent of the upland portion of the nearshore zone is unquantified and still requires directed research to define.

Broadscale patterns in Washington state's saltwater shoreline habitats have recently (1995-2000) been characterized under the Washington Department of Natural Resources ShoreZone mapping system (WA Department of Natural Resources 2000, Berry et al. 2001). The resultant GIS data set characterizes important physical, biotic, and anthropogenic features that can be considered indicators of ecosystem health. The abundance and distribution of these features varies along environmental and human-use gradients. This information represents an important baseline inventory of existing conditions, and may be used to identify areas of high-quality or degraded nearshore habitats throughout the region.

Estuaries are commonly found where rivers enter marine waters, and may include the lower, tidal reaches of rivers (Pritchard 1967). A common definition of an estuary is "waters that are semi-enclosed by land but have open, partly obstructed, or sporadic access to the ocean, and in which seawater is at least occasionally diluted by freshwater runoff from land" (Dethier 1990). Estuaries extend upstream or landward to where ocean-derived salts measure <0.5 parts per thousand (ppt), and downstream or out to sea to where freshwater dilution is minimal (>30 ppt).

Under this definition, estuaries include classic river-mouth and delta systems, lagoons, and large bodies of water such as Puget Sound and the Strait of Georgia, which experience significant dilution from many sources. In inland Washington's Puget trough, many areas such as the San Juan Islands are difficult to categorize as either estuarine or marine because surface salinities, nutrient levels, and circulation are temporally influenced by seasonal patterns of freshwater runoff and tidal flows.

Both estuarine and nearshore marine habitats are located within a transition zone between land and sea and are incredibly dynamic environments influenced by constantly changing physical, chemical, and biological processes. Overviews of the geology and natural coastal processes of these habitats in Puget Sound are provided in Downing (1983) and Terrich (1987).

Estuarine and Nearshore Marine Habitat Descriptions and Functions

Washington state marine shorelines can be grouped into three distinct regions: the shores of the inland coastal waters of Puget Sound and the Strait of Juan de fuca (2246 mi); the outer coast fronting the Pacific Ocean (171 mi); and the shores of outer coast estuaries (313 mi) (Hagen 1958). Estuarine and nearshore marine habitats can take many forms, including eelgrass (especially *Zostera marina*) meadows, kelp forests, sand and mudflats, tidal marshes, river mouths and deltas, sand spits, beach and backshore areas, banks and bluffs, and marine riparian areas (Dethier 1990) (Figure 1). These habitats perform a variety of important functions within an ecosystem and play a critical role in the life history and ecology of commercially and ecologically important resources in the region. A classification system for these habitat types in Washington State was developed by Dethier (1990) and largely corresponds to locally prevalent physical processes, such as wave energy, depth, tidal elevation, substratum type, and several modifiers (Appendix A). For each combination of these physical variables, plant and animal species diagnostic of these habitats are described, based on surveys from around the state.

Estuarine systems encompass a variety of habitats, including tidally-inundated vegetated marsh areas. General tidal marsh functions encompass those commonly listed for wetlands, which include: primary production, fish and wildlife support, groundwater recharge, nutrient cycling, flood attenuation, and water quality improvement (Simenstad 1983). Common tidal marsh plants of Washington include Lyngby's sedge (*Carex lyngbyei*), Salt grass (*Distichlis spicata*), Baltic rush (*Juncus balticus*), American three-square bulrush (*Scirpus americanus*), maritime bulrush (*S. maritimus*), arrowgrass (*Triglochin maritimum*), tufted hairgrass (*Deschampsia caepitosa*), pickleweed (*Salicornia virginica*), Pacific silverweed (*Potentilla pacifica*), red fescue (*Festuca rubra*), and common reed (*Phragmites* sp.) (Simenstad 1983, Simenstad et al. 1991a, Dethier 1990). Primary production rates for regional tidal marshes range from 529-1,108 g C m^{-2} yr^{-1} (Thom 1981). Juvenile salmon have been shown to reside in tidal marshes and exhibit substantial growth while foraging on prey resources both produced in, and imported to, the marsh system (Shreffler et al. 1992, Simenstad and Cordell 2000).

Figure 1. Typical nearshore marine habitats found in Washington State (from King County DNR).

Eelgrass is an example of a regional resource that provides a number of widely recognized and valued functions, including primary production, nutrient processing, wave and current energy buffering, organic matter input, habitat for fish and invertebrates, and food for birds (Phillips 1984). Eelgrass forms small patches to large meadows in the low intertidal and shallow subtidal zone in both estuaries and protected nearshore marine habitats. Its productivity can equal or exceed the productivity rates of most other aquatic plants, with rates reported in the Pacific Northwest ranging from 200-806 g C m^{-2} yr^{-1} (Thom 1984, Kentula and McIntire 1986, Thom 1990). Organic carbon produced by eelgrass can enter the food web through the microbial decomposition and processing of both particulate and dissolved eelgrass materials. This organic matter has been shown to be incorporated in the diet of fish and other marine animals including juvenile salmon (Simenstad et al. 1988). There is a rich epiphytic flora and associated small invertebrate fauna that forms seasonally on eelgrass leaves. As well, juvenile salmonids may use eelgrass for feeding and rearing, and herring (*Clupea harengus pallasi*) use eelgrass as a spawning substrate.

Bull kelp (*Nereocystis luetkeana* (Mertens) P. & R.) is a brown alga that forms small patches to large forests in the shallow subtidal zone in Puget Sound and contributes important primary production to pelagic and nearshore food webs. Its complex structure also provides refuge and feeding habitat for fishes (especially rockfishes; (West et al. 1995, Buckley 1997), spawning substrate for herring, and buffering of wave and current energy (Duggins 1980, Harrold et al. 1988, Jackson and Winant 1983).

Flats, sand spits, and backshore habitats generally include gently sloping sandy or muddy beaches, with substrata that may be composed of a mixture of mud (substrata <0.06 mm diameter, usually mixed with organics), sand (0.06-4 mm), gravel (pebbles 4-64 mm)), and cobble (rocks between 64 mm - 256 mm) (Dethier 1990). Sand and mudflats provide a number of functions, including primary production (primarily by microalgae such as diatoms); nutrient cycling; prey production for juvenile salmon, flatfish, and birds; and bivalve production. Juvenile salmon prey species (e.g., harpacticoid copepods) have been shown to be seasonally abundant on flats and their distribution is linked to benthic microalgal abundances (Thom et al. 1989). A number of fishes, including forage fish such as surf smelt (*Hypomesus pretiosus)* and Pacific sand lance (*Ammodytes hexapterus*) (Pentilla 1995) spawn on mixed sand-gravel beaches Puget Sound (Lemberg et al. 1997). Shorebirds are commonly observed feeding on invertebrates produced on flats in the Pacific Northwest (Herman and Bulger 1981). Two taxa of seaweed, *Ulva* spp. and *Fucus gardneri*, predominate on beaches in the region either attached to more stable rocks (primarily *Fucus gardner*) or free-floating in viable patches deposited along the beach (*Ulva* spp.). Production rates by seaweeds on cobble shorelines can be as high as eelgrass meadows (Thom et al. 1984). Bivalve production is often high on cobble and gravel beaches where adequate organic matter deposition occurs.

Large woody debris (LWD) generally accumulate in backshore areas at extreme high tides, and can help stabilize the shoreline (Zelo and Shipman 2000, Macdonald et al. 1994). Although not well documented in marine systems, LWD provides structurally complex roosting, nesting, refuge, and foraging opportunities for wildlife; foraging, refuge, and spawning substrate for fishes; and foraging, refuge, spawning, and attachment substrate for aquatic invertebrates (Brennan and Culverwell, In Prep). Logs imbedded in beaches also provide a source of organic matter, moisture, and nutrients that assist in the establishment and maintenance of dune and marsh plants.

Banks and bluffs are steeply sloping areas (e.g., cliffs) located between the intertidal zone and the upland. Banks and bluffs can be comprised of sediments of varying grain sizes, as well as rock and bounders. While not extensively studied, the functions performed by banks and bluffs include providing protection to uplands, sediment supply to beaches (Macdonald et al. 1994), habitat for bluff-dwelling animals (including nesting birds), and groundwater supply into estuarine and marine waters. These habitats are maintained by the dynamics of several forces including wave energy, surface runoff, and stabilizing vegetative cover (Macdonald et al. 1994, Myers 1993, Manashe 1993).

Marine riparian habitats occur at the interface between terrestrial and aquatic ecosystems. They are characterized by dense vegetation that may include Sitka spruce (*Picea sitchensis*), willow (*Salix* spp.), red alder (*Alnus rubra*), black cottonwood (*Populus trichocarpa*), roses (*Rosa* spp.), and Douglas spirea (*Spirea douglasii*) (Simenstad et al. 1991a, Battelle et al. in review). Riparian vegetation affects the quality of aquatic habitats by increasing slope stability, providing erosion protection (Myers 1993, Manashe 1993, Broadhurst 1998), and buffering against pollution and sediment runoff (Federal Interagency Stream Restoration Working Group 1998). Marine riparian vegetation also performs a number of increasingly recognized habitat functions at the interface between aquatic and terrestrial zones (Brennan and Culverwell in prep). For example, overhanging riparian vegetation provides shading that regulates microclimates important to intertidal invertebrate distribution (Foster et al. 1986) and surf smelt spawning (Pentilla 2000). Vegetated riparian zones deliver organic matter and invertebrate prey to the nearshore (Simenstad and Cordell 2000), and creates complex structure that is important for fish (e.g., refuge and spawning) and wildlife (e.g., bird nesting and roosting) (Battelle et al. in review).

Definition and Overview of Shoreline Modifications and Restoration

Human shoreline modifications are commonly designed and built to dissipate wave energy, maintain navigation channels, control shoreline erosion, repair storm damage, protect from flooding, store or accumulate sediment, and promote commercial or recreational activity (see (U.S. Army Corps of Engineers 1984b, Cox et al. 1994). The location and functional design of shoreline modifications often parallels the likely range of impacts to the nearshore physical processes and biota, and provides a logical way for organizing the broad range of these modification activities (Table 1). Although some structures may perform multiple functions, the description of estuarine and nearshore marine modification activities is treated throughout the remainder of this paper based on these three primary functional design categories: wave energy dissipation, shoreline stabilization, and other human needs. Breakwaters and jetties project into subtidal areas and are designed to dissipate wave energy, protect backshore areas, and direct tidal flow. Shoreline armoring or stabilization methods include bulkheads, revetments, seawalls, groins, ramps, beach nourishment, and biotechnical approaches. Finally, shoreline or nearshore structures such as tide gates, sewer outfalls, and artificial reefs provide for other human needs (e.g., farmland creation, runoff and waste conveyance, fishing and diving opportunities) and directly affect nearshore hydrology in other ways.

Table 1. General design functions of common shoreline structures.

Function	Structural Modification
Wave Energy Dissipation	Breakwaters, Jetties
Shoreline Stabilization	Bulkheads, Revetments, Seawalls, Groins, Ramps, Beach Nourishment, Biotechnical Measures
Other Human Needs	Tide gates, Outfalls, Artificial Reefs

Washington State, and in particular the greater Puget Sound area, have experienced rapid population and economic growth in recent decades. King County was one of the United States' leading (top 10) coastal counties in both residential and office construction from 1970-1989 (Culliton et al. 1992), a building boom that has continued apace since those figures were published. As a result of this growth, by 1980 it was estimated that 32% of historic intertidal wetlands and 73% of historic subaerial wetlands bordering Puget Sound had been lost (Bortleson et al. 1980). Over 29% of Puget Sound's shoreline is stabilized by structures, with 1.7 miles of Puget Sound shoreline being newly armored each year (Canning and Shipman 1995b). In King County watershed resource inventory areas (WRIAs) 8 and 9 alone, recent surveys have shown that armoring comprises 75-87% of the coastline (Washington Department of Natural Resources 1999, Battelle et al. in review). Besides simplifying shorelines and reducing intertidal habitat area (see Douglass and Pickel 1999), these modifications have direct effects on nearshore processes and the ecology of myriad species (Macdonald et al. 1994, Thom et al. 1994a). Shoreline modifications also affect salmon habitat by reducing shallow water areas and nearshore functional benefits, a particular concern because of the cultural and economic significance of salmon to the region (National Research Council 1996).

As human populations grow and impacts to the natural environment compound and are realized, habitat restoration is attracting increasing attention as a remedy to these problems. Restoration is defined as "the return of an ecosystem to a close approximation of its condition prior to disturbance…The goal is to emulate a natural, functioning, self-regulating system that is integrated with the ecological landscape in which it occurs." (National Research Council 1992). Although restoration approaches are generally improving, there is much to be gained through very careful planning and adaptive implementation of restoration projects in the region (Thom 2000). Monitoring the performance of restored systems, and baseline studies in reference areas, are critical to the development of appropriate restoration strategies (Battelle et al. in review).

Estuarine and Marine Nearshore Habitat Use By Living Resources

All nearshore marine and estuarine habitats have some connection to fisheries and wildlife resources in the region. Two locally relevant reference documents provide a good basis for determining functional linkages between habitats and these living resources. Dethier (1990) lists plant and animal species commonly associated with estuarine and nearshore marine habitats throughout Washington State (Appendix A). Simenstad et al. (1991a) further assess the functions of estuarine wetlands and associated nearshore habitats to 105 fish and wildlife species in Puget Sound, guided by available literature and expert knowledge (Appendix B). In this publication, a functional link between a habitat and a species is generally demonstrated via feeding, refuge from predation or disturbances, or support of reproduction. It should be noted that species' habitat requirements may change depending on life history stage. We briefly review estuarine and nearshore habitat requirements of a number of commercially important fish species in Washington State.

Salmonids

Salmon in the Pacific Northwest are often used as biological indicators for the ecological health of an area because they integrate a variety of habitats throughout their life history. Their functional relationships with other species in estuarine and nearshore marine zones provide some measure of the interconnectedness of these habitats (cf. Simenstad and Cordell 2000). Likewise, estuarine and the nearshore marine habitats are integral to the survival and growth of salmonids and many other fish and wildlife species (Simenstad 1983, Simenstad et al. 1991a, Thom 1987, Spence et al. 1996), and these functions may be compromised by shoreline modifications (Table 2).

Table 2. Functions of estuaries and nearshore systems for salmon, and potential effects of shoreline modification.

Function	Potential Effects of Shoreline Modification
Migration	▪ Corridors of movement blocked ▪ Connections between habitats fragmented ▪ Critical habitats in the landscape are eliminated
Nursery	▪ Shallow water areas reduced ▪ Vegetation cover lost
Juvenile Food Production and Feeding	▪ Habitats that produce prey are lost or degraded ▪ Access to prey resources are blocked ▪ Drift material accumulation areas are lost
Adult Food Production	▪ Habitats that produce prey are lost or degraded ▪ Access to prey resources are blocked ▪ Baitfish spawning habitat degraded
Residence	▪ Refuge habitats are lost or fragmented
Physiological Transition	▪ Hydrological changes alter/restrict location of physiological adjustment

All juvenile salmon move along the shallows of estuaries and nearshore areas during their outmigration to the sea, and may be found in these habitats throughout the year depending on species, stock, and life history stage (Table 3) (Emmett et al. 1991, Spence et al. 1996). Shallow estuarine and nearshore habitats are structurally complex (e.g., submerged aquatic vegetation and LWD), highly productive, and dynamic. As such, they are critical areas for juvenile salmonids because they provide food, refuge from predators, and a transition zone to physiologically adapt to salt water existence (Mason 1970, Macdonald et al. 1987, Thorpe 1994, Levings 1994, Spence et al. 1996). Juvenile salmonids behaviorally restrict their movements to shallow water (between 0.1 and 2.0 m) until they reach larger sizes that may allow them to exploit deeper channel and open-water habitats and associated prey resources. Returning adult salmon and some resident stocks use nearshore habitats as feeding areas where they consume forage fish such as Pacific herring (*Clupea harengus pallasi*), surf smelt (*Hypomesus pretiosus*), and sand lance (*Ammodytes hexapterus*) (Pentilla 1995, Brodeur 1990, Fresh et al. 1981). Adult salmon may delay their entry into freshwater or into terminal spawning areas at the end of the marine phase of their life cycle, "milling" within estuary and nearshore habitats for up to 21 days (Johnson et al. 1997).

Juvenile chum (*Oncorhynchus keta*) and chinook salmon (*O. tshawytscha*) are considered the most estuarine-dependent salmon species, feeding and rearing in these habitats for extended periods before migrating to pelagic marine habitats (Levy and Northcote 1982, Simenstad et al. 1982, Levings 1994, Cordell et al. 1997, Levings et al. 1991, , Warner and Fritz 1995, Aitkin 1998)) (Table 3). It may be emphasized that two salmon stocks (fall chinook and summer chum salmon) federally listed as threatened under the Endangered Species Act in Puget Sound, are also the most estuarine/shoreline dependent species/stocks in the region (Table 3). The bulk of juvenile chum and ocean-type chinook salmon outmigration occurs in the spring (March through May), but juveniles may spend days to months in estuarine and nearshore marine habitats depending on rearing conditions (Wallace and Collins 1997, Levy and Northcote 1982, Emmett et al. 1991). Chum salmon fry migrate seaward almost immediately after hatching, and enter the estuary at a relatively small size (30-55 mm), while chinook fry migrate seaward either soon after yolk resorption (30-45 mm), as fry 60-150 days post-hatching, or as fingerlings. Both species prefer relatively fine-grained substrate and low stream gradients, and are oriented to shallow water habitats located close to shore. Chum fry tend to use the middle or lower parts of the estuary, whereas chinook fry tend to rear for prolonged periods in the upstream edge of the estuary, feeding on floating insects in tidal fresh and brackish marshes (Thom et al. 1994a). As juvenile chinook grow, they move downstream to tidal flats (+2 to –2 MLLW), and channels (below MLLW) where they shift to epibenthic prey (Thom et al. 1994a). Both species may forage extensively in upper elevations of saltmarshes during high tide, where they gain a large percentage of their daily caloric intake.

In most systems, juvenile coho salmon (O. kisutch) generally spend 12-18 months rearing in freshwater before migrating through the estuaries and into marine waters (Levy and Northcote 1982, Weitkamp et al. 1995) (Table 3). However, early outmigrating coho fry (age-0 fry or pre-smolts) also may feed and rear in productive estuarine habitats for extensive periods (up to 114 days) (Miller and Sadro, unpublished report). This life-history strategy may be especially prevalent in coastal populations residing in streams with seasonal low flows and elevated temperatures. Coho smolts are generally much larger than chinook and chum juveniles in nearshore areas and it is thought they prefer deep, marine-influenced habitats (Emmett et al. 1991). Yet, they are often caught in beach seines over intertidal and pelagic habitats in estuaries and over shallow nearshore marine habitats such as eelgrass meadows and tideflats (Mavros and Brennan 2001).

Other salmon species use nearshore marine habitats to varying degrees. For instance, pink salmon (*O. gorbuscha*) up to 60-80 mm in length migrate through and rear extensively in shallow marine waters and nearshore embayments from March until June, feeding on small crustaceans and growing rapidly (Emmett et al. 1991, Levy and Northcote 1982, Hard et al. 1996) (Table 3). They spend little time in estuarine areas but may be abundant in estuarine tidal channels for a short time. Coastal cutthroat trout juveniles and adults (*O. clarki*) can be found over a variety of substrates within nearshore marine and estuarine waters during the spring to fall (Emmett et al. 1991, Gregory and Levings 1996). Gravel beaches with upland vegetation, and nearshore habitats (<10 ft deep) with LWD are often used by cutthroat trout during their marine phase for feeding and migration (King County Department of Natural Resources and R2 Resource Consultants 2000). Coastal cutthroat trout rarely overwinter in saltwater, and can be found in tidal freshwater areas of estuaries as they await favorable conditions to go upstream (Emmett et al. 1991, Johnson et al. 1999). Ongoing research is gradually clarifying the distribution and abundance of bull trout (*Salvelinus confluentus*) in Puget Sound estuaries and nearshore waters (WDFW 1994, King County DNR and R2 Resource Consultants 2000). In the Skagit River basin, most char smolts outmigrate between April and July, rearing for the summer in estuarine and nearshore waters before moving back into freshwater to overwinter (C. Kraemer, WDFW, pers. communication). While in nearshore marine areas, char of all ages are typically associated with shallow water, especially in areas of forage fish concentrations (i.e., surf smelt (*Hypomesus pretiosus*) spawning beaches) (C. Kraemer, WDFW, pers. communication).

Other salmonid species less recogized for estuarine dependence are nonetheless reliant on the protective cover of natural nearshore habitats for migration (Table 3). For example, sockeye salmon (*O. nerka*) smolts outmigrate to the ocean under cover of darkness in the spring to early summer and usually have a shorter residence time in estuaries and nearshore areas than other salmonids (Hart 1973, Emmett et al. 1991, Gustafson et al. 1997). Adult steelhead (*O. mykiss*) are epipelagic and found in coastal neritic waters to a depth of 25 m (Emmett et al. 1991). Like sockeye, juvenile steelhead usually move to sea from April through June (Busby et al. 1996) and appear to spend little time in estuaries (Emmett et al. 1991). Juvenile steelhead in Puget Sound are periodically collected in beach seines over shallow nearshore marine habitats, such as eelgrass meadows and tideflats (Mavros and Brennan 2001).

Many of the declines in salmonid populations are likely attributable to urbanization and anthropogenic activities in nearshore marine and estuarine habitats (Schmitt et al. 1994). Loss of over 70 percent of Puget Sound coastal wetlands and estuaries to urban or agricultural development (diking, dredging, and hydromodification) has resulted in a massive reduction in rearing habitat for juveniles, especially estuarine-dependent chum and chinook salmon and cutthroat trout (Myers et al. 1998). Degradation and loss of shallow vegetated habitats may alter sheltered migration corridors for juveniles of all species (Simenstad et al. 1982). Declines in woody debris in estuaries and shoreline alterations have likely resulted in detrimental effects to many resident and migratory stages due to a reduction in refuge and feeding sites (Johnson et al. 1999). Shoreline armoring, over-water structures that shade marine vegetation and alter primary productivity, filling, channel dredging, and pollution from upland commercial, industrial, and residential development may also be contributing to the declines.

Table 3. Summary of nearshore marine and estuarine habitat use by salmonid species and federal status of stocks in Washington State.

			Nearshore Marine and Estuary Use [a]		
Common Name	Scientific Name	Federal Stock Status	Adult Residence	Adult and Juvenile Migration	Juvenile Rearing
Chinook Salmon	*Oncorhynchus tshawytscha*	Threatened – Puget Sound ESU	●	●	●
Chum Salmon	*Oncorhynchus keta*	Threatened – Hood Canal ESU	○	●	●
Coho Salmon	*Oncorhynchus kisutch*	Candidate – Puget Sound / Georgia Strait ESU	⊕	●	⊕
Sockeye Salmon	*Oncorhynchus nerka*		○	●	○
Pink Salmon	*Oncorhynchus gorbuscha*		○	●	●
Cutthroat Trout	*Oncorhynchus clarki*		●	●	●
Steelhead	*Oncorhynchus mykiss*		○	●	⊕
Bull trout	*Salvelinus confluentus*	Threatened – Coastal - Puget Sound DPS	●	●	●

[a] Filled circles represent extensive use, cross-filled circles represent some use, and open circles indicate little or unknown use in these areas.

Forage Fish

Forage fish, as the name implies, are a significant part of the prey base for marine mammals, sea birds, and predatory finfish populations in Washington State. Forage fish include a variety of small, schooling species, and are a valuable indicator of the health and productivity of the marine environment (Lemberg et al. 1997). In turn, they are reliant upon a variety of shallow nearshore and estuarine habitats (Table 4). The major forage fish species in nearshore waters of Washington State include Pacific herring (*Clupea harengus pallasi*), surf smelt (*Hypomesus pretiosus*), and sand lance (*Ammodytes hexapterus*) (Pentilla 1995), all three of which lay eggs in shallow, intertidal vegetated or sand-gravel beach habitats (Cardwell and Koons 1981). Longfin smelt (*Spirinchus thaleichthys*) is an anadromous species found throughout estuarine habitats (especially outer coast systems) within Washington State (Emmett et al. 1991).

Eighteen discrete herring stocks are present in Puget Sound, each with annual spawning runs to specific nearshore areas. Current data are insufficient to determine whether surf smelt and sand lance have discrete spawning populations in nearshore areas (Lemberg et al. 1997). The maintenance of healthy and viable forage fish stocks is dependent on preservation of these critical spawning habitats and adjacent riparian areas (Pentilla 1978, Washington Department of Fisheries 1974).

Table 4. Summary of nearshore marine and estuarine habitat use by forage fish species and federal status of stocks in Washington State.

			Nearshore Marine and Estuary Use [a]		
Common Name	Scientific Name	Federal Stock Status	Adult Spawning	Residence & Migration	Juvenile Rearing
Pacific Herring	*Clupea harengus pallasi*	Candidate – Puget Sound ESU	●	●	●
Surf Smelt	*Hypomesus pretiosus*	Unknown	●	●	●
Longfin Smelt	*Spirinchus thaleichthys*	Unknown	●	●	●
Sand Lance	*Ammodytes hexapterus*	Unknown	●	●	●

Source: Lemberg et al. 1997; Musick et al. 2000
[a] Filled circles represent extensive use, cross-filled circles represent some use, and open circles indicate little or unknown use in these areas.

Groundfish

Groundfish live in marine waters and spend their lives near or on the bottom. In Washington State, groundfish are legally defined as food fishes, and most are the focus of important fisheries (Palsson 1997). Groundfish include the true cods (Pacific cod (*Gadus macrocephalus*), walleye pollock (*Theragra chalcogramma*), and Pacific hake (*Merluccius productus*)), lingcod (*Ophiodon elongatus*), flatfish, and rockfish (Table 5). Populations of several stocks, particularly Pacific cod and hake, are at historic lows in Washington State. Rockfish (*Sebastes* sp.), as their name implies, are often associated with subtidal rocky reefs. More than 20 species of rockfish inhabit Puget Sound, but copper (*Sebastes caurinus*), quillback (*S. maliger*), brown (*S. auriculatus*), and black rockfish (*S. melanops*) are the four most common species found in Puget Sound's shallow nearshore marine habitats (West 1997).

While some adult groundfish reside within deeper marine waters, most rely on shallow nearshore marine and/or estuarine habitats during part of their life history (Table 5). Shallow vegetated nearshore habitats are particularly important as nursery areas for the early life history stages of these species. Consequently, these species are susceptible to the loss of critical nearshore habitat for settlement, feeding, and refuge and are likely susceptible to fragmentation of the links between nearshore marine habitats that are critical to various life history stages. Rockfish may be locally abundant in some locations in Puget Sound, generally near kelp or rocky habitat, but are prone to severe depletion from overfishing due to their habitat specificity.

The cods (gadids) typically spawn en masse in offshore areas, straits, or the deeper portion of bays. Pacific cod and walleye pollock larvae metamorphose and settle to shallow vegetated or gravel/cobble habitats, where they find shelter and prey resources (Schmitt et al. 1994). Juvenile and immature hake may aggregate in inshore waters and mainland inlets, where they feed and grow away from concentrations of adults. Shallow, rocky, nearshore areas are significant areas for adult lingcod nesting (although evidence of nesting activity has been reported at depths up to 100m) (B. Pacunski, WDFW, personal communication). Juvenile lingcod move to benthic habitats in late spring-early summer, settling in shallow water vegetated kelp or eelgrass habitats (West 1997). Age 1-2 lingcod are commonly observed in high-current, soft bottom, or shell hash habitats near the mouths of bays and estuaries (D. Doty, WDFW, personal communication). Adult English sole spawn offshore in deep water aggregations; however, juvenile English sole use a variety of shallow nearshore marine and estuarine habitats, and tend to prefer shallow (<12 m deep) muddy substrates (Emmett et al. 1991). Juvenile English sole exhibit distinct patterns of depth segregation, with smaller fish generally restricted to shallow waters and larger fish being found progressively deeper. Eggs of rock sole have recently been identified from sand-gravel upper intertidal beaches at a number of sites in Puget Sound (Pentilla 1995). Juveniles and adult rock sole are abundant in nearshore marine habitats at depths $\leq$ 15 m.

Table 5. Summary of nearshore marine habitat use by important groundfish species and federal status of stocks in Washington State.

			Nearshore Marine Use [a]		
Common Name	Scientific Name	Federal Stock Status	Adult Spawning	Residence & Migration	Juvenile Rearing
Pacific Cod	*Gadus macrocephalus*	Candidate		●	●
Walleye Pollock	*Theragra chalcogramma*	Candidate		●	●
Pacific Hake	*Merluccius productus*	Candidate		●	●
Lingcod	*Ophiodon elongatus*	Candidate	●	●	●
English Sole	*Pleuronectes vetulus*	None		●	●
Rock Sole	*Lepidopsetta bilineata*	None	●	●	●
Black Rockfish	*Sebastes melanops*	None	●	●	●
Brown Rockfish	*Sebastes auriculatus*	Candidate	●	●	●
Copper Rockfish	*Sebastes caurinus*	Candidate	●	●	●
Quillback Rockfish	*Sebastes maliger*	Candidate	●	●	●

Source: Palsson 1997; Musick et al. 2000
[a] Filled circles represent extensive use of these areas.

Nearshore areas are important spawning habitats for rockfishes, with females moving into shallow waters during the spring, when parturition occurs (B. Pacunski, WDFW, personal communication). Born as free-swimming pelagic larvae, rockfish spend two to four months in the water column feeding on small zooplankton. When the planktonic larvae reach a specific size they move to shallow, benthic nursery habitats (West 1997). Drift material in the pelagic zone, including dislodged nearshore vegetation, provides prey resources and refugia that links larval rockfish settlement to the nearshore environment (Buckley 1997). Studies of the more common copper, quillback, and brown rockfish species indicate that shallow areas with eelgrass, kelp beds, and other vegetation on cobbles and boulders are used as nursery habitats (West 1997). These nearshore habitats provide juvenile rockfish shelter from predation and increased access to prey resources. Limited availability of such habitat is thought to impose a demographic bottleneck on stock recruitment. Temperature affects juvenile rockfish growth during their first year, with warmer temperatures such as those found in the nearshore areas producing higher growth rates and possibly increasing their food assimilation efficiency (Buckley 1997).

Nearshore Food Webs

Comprehensive studies in northern Puget Sound and the Strait of Juan de Fuca have synthesized biological data and analyzed food web relationships of organisms in nearshore marine habitats (Simenstad et al. 1979; Long 1982). Food webs in shallow water nearshore habitats are largely based on the heterotrophic processing of detritus produced by senescing marine algae, estuarine and saltmarsh vascular plants, and especially eelgrass (Figure 2) (Long 1982). In general, food web complexity in these systems increases with decreasing exposure, decreasing sediment particle size, and increasing deposition of algal and vegetative detritus (Simenstad et al. 1979).

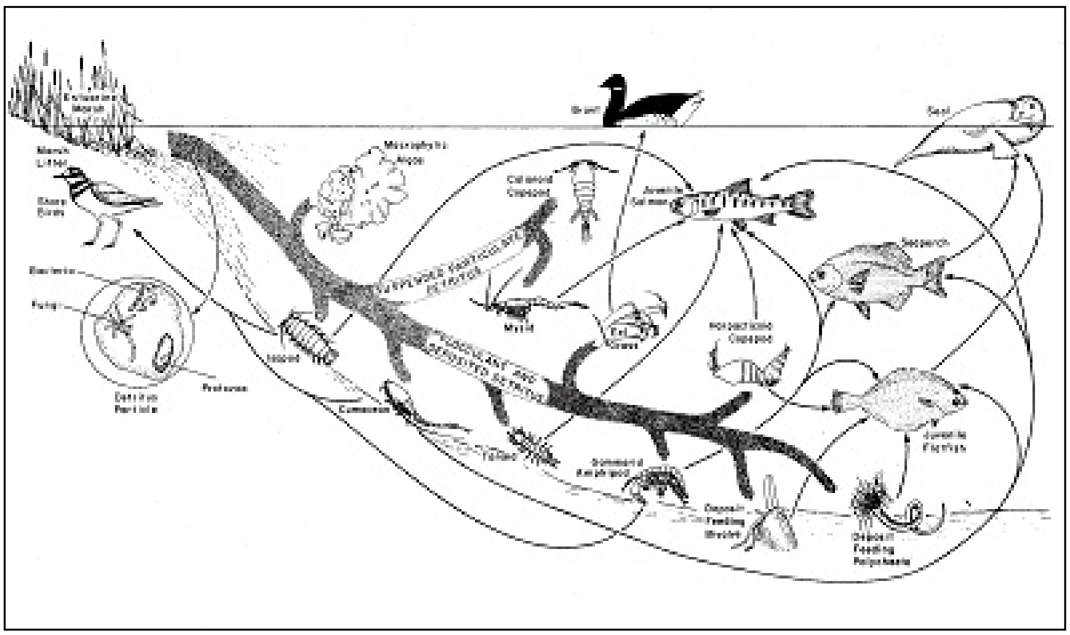

Figure 2. Simplified example of a detritus-based shallow subtidal food web in Northern Puget Sound (Long 1982)

Simenstad et al. (1979) constructed composite food webs for seven representative nearshore habitats: neritic, rocky/kelp bed sublittoral, rocky littoral, cobble littoral, and shallow sublittoral zones of gravel-cobble, sand-gravel/eelgrass, and mud/eelgrass habitats. Calanoid copepods and gammarid amphipods were recognized as being critical to upper trophic levels in most shallow sublittoral zones because they provide food resources for important consumer organisms or they convert organic matter to make it available to higher level consumers (e.g., detritus processors).

In turn, they are the primary prey of important secondary consumers such as Pacific herring, Pacific sand lance, and juvenile Pacific salmon, which are used by higher level carnivores.

The principal secondary consumers in shallow neritic habitats (i.e., surface waters and water column of the nearshore region) of northern Puget Sound/Strait of Juan de Fuca are schooling fishes such as juvenile Pacific herring, Pacific sand lance, northern anchovy, longfin smelt, and surf smelt (Simenstad et al. 1979). Almost all marine birds and mammals found in neritic habitats are tertiary consumers that feed on these forage fish species. Secondary consumers in rocky sublittoral and associated kelp habitats are typically demersal or bottom-oriented fishes, including greenlings, gunnels, sculpins, rockfishes, and gobies, and gastropods, octopus, and a variety of seastars. In turn, harbor seals, northern sea lions, and orcas prey upon larger demersal fishes. In gravel-cobble shallow sublittoral habitats, important secondary carnivores are primarily juvenile and adult flatfish, including English sole and rock sole. Benthic-feeding shorebirds, such as greater yellowlegs, sanderling, great blue heron, and sandpipers, are prevalent in this habitat, as well as protected sand/eelgrass and mud/eelgrass habitats. Mud/eelgrass habitats, commonly associated with saltmarsh environments, are considered the most complex and highly connected food webs. Besides many of the fish species already mentioned, juvenile salmon (especially chum), staghorn sculpin (*Leptocottus armatus*), crescent gunnel (*Pholis laeta*), pipefish (*Syngnathus* spp.), various flatfish species, and shiner perch (*Cymatogaster aggregata*) are the predominant secondary consumers in these protected shallow water habitats.

Conceptual Framework for Assessing Impacts

Nearshore marine and estuarine habitats operate at the edge of the terrestrial and aquatic marine environments, and involve complex interactions within and between these diverse habitats. In this context, two complementary approaches are usually combined to interpret the ecological impacts of structural shoreline modification: 1) A conceptual approach involving inferences based on an informed understanding of the ecosystem and its processes, and 2) a direct approach that documents cause-and-effect through biological study. In this section, we present an overview of a framework for approaching these issues, which conceptualizes the predominant impacts that shoreline modifications have on the functionality of estuarine and nearshore marine habitats. In the next section we provide a summary of direct studies related to particular types of shoreline modifications, and review inferential evidence that links locally relevant shoreline modification activities to resource impacts.

The conceptual approach uses a model that identifies the linkages between habitat features and potential impacts of shoreline modification. The model, in its simplest form, is shown in Figure 3.

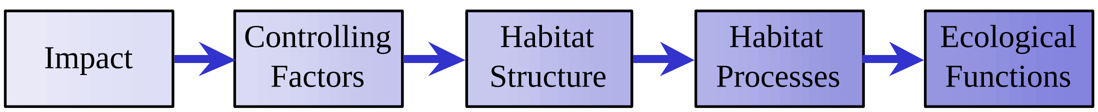

Figure 3. Conceptual model linking shoreline impacts to ecological functions.

We assume that shoreline modifications will exert effects at varying degrees on an ecosystem's controlling factors. Controlling factors are physical processes or environmental conditions that control local habitat structure and composition (e.g., vegetation, substrate), including where habitat occurs and how much is present. In turn, habitat structure is linked to support processes, such as shading or cover, which are linked to ecological functions. Thus, impacts that affect controlling factors within an ecosystem will be reflected in changes to habitat structure, and will ultimately be manifested as changes to functions supported by the habitat. The effect at the functional level depends upon the level of disturbance and the relative sensitivity of the habitat to the disturbance.

Impact Types and Controlling Factors

An impact is defined as an unnatural disturbance of habitat controlling factors. Any structural modification of the shoreline will alter several important physical processes, and can therefore be considered an impact. For the most part, impact potential can be related to the size and location of the structure and the types of physical processes it alters.

Impacts may be considered direct or indirect (Table 6). Direct impacts are generally associated with construction activities, including excavation, burial, and various types of pollution. Indirect impacts occur following physical disturbance, and are chronic in nature due to permanent alteration of physical processes such as sediment transport and wave energy. "Cumulative impacts" are associated with increasing number or size of indirect or direct impacts, which can have either linear or non-linear cumulative responses. For example, increasing the length of shoreline that is armored within a drift cell may result in no impact to sediment deposition or accretion on adjacent beaches until the length of armored shoreline reaches a critical point. After this point, additional armoring results in major loss of sediment supply to the beaches in the drift cell. Although non-linear or threshold responses like this are theoretically possible, there are no studies that evaluate this type of response in nearshore marine and estuarine habitats. A complex, cumulative impacts model would be more appropriate for assessing effects on biological resources in fragmented habitats of highly modified urban industrial estuaries (e.g., Elliott Bay and Commencement Bay).

Table 6. Effects of shoreline armoring and restoration on physical processes (adapted from Macdonald et al. 1994).

Direct Impacts 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

By their very nature and design, shoreline structures alter physical processes (Rensel 1993) by modifying hydraulic forces and controlling sediment movement and supply. Macdonald et al.

(1994) related the severity of beach impacts to various shoreline armoring approaches (Figure 4). Qualitatively, wave reflection forces increase as armoring methods intensify, with higher impacts to beach processes in areas with vertical seawalls or bulkheads, and lower impacts in areas using graded structures or "soft" solutions (i.e., beach nourishment).

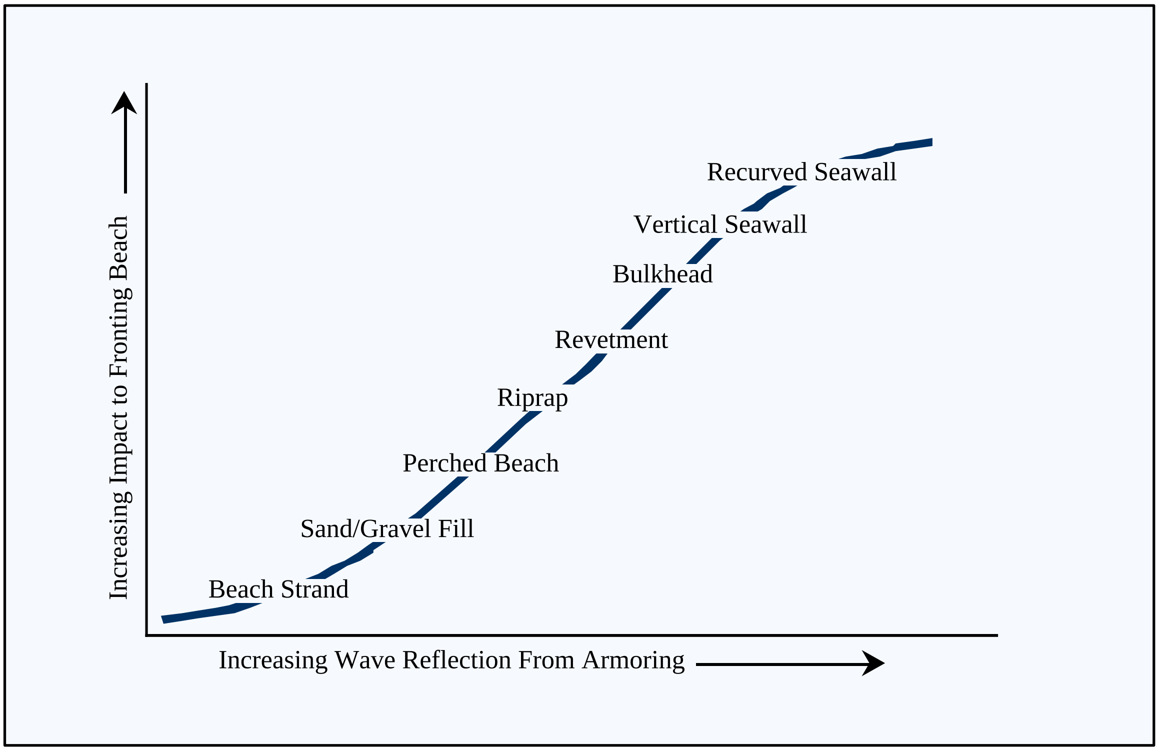

Figure 4. Relative beach impact by shore protection method (from Macdonald et al. 1994).

Habitat Controlling Factors, Structure, and Function

Controlling factors such as water depth (elevation), substrate type, light level, and wave energy are the most important parameters influencing the development, distribution, and maintenance of nearshore habitats (Table 7). Yet, we have only recently begun to quantify the relationships between controlling factors and habitat structure and function (Thom 2000). We know, for example, that depth (elevation) is highly correlated with the distribution of intertidal species. We also know that interspecific competition and natural disturbances are important in regulating both the vertical distribution as well as the spatial patchiness of biota (e.g., Paine 1979). Our level of understanding, or lack thereof, mediates the confidence we have in making predictions about potential impacts that shoreline modification and restoration actions may have on habitat structure and function. In general, far more work is needed to quantify the fundamental relationships between habitat conditions and controlling factors for the nearshore environment in Washington State.

Table 7. List of major habitat controlling factors, habitat structure and function metrics.

Controlling Factors	Habitat Structure	Habitat Functions	Ecological Functions
▪ Dept ▪ Substrata ▪ Slope ▪ Light ▪ Wave Energy ▪ Hydrology ▪ Temperature ▪ Salinity ▪ Nutrients ▪ Water Quality	▪ Density ▪ Biomass ▪ Individual Lengths ▪ Diversity ▪ Patch Size ▪ Patch Shape ▪ Landscape Position	▪ Production ▪ Sediment Flux ▪ Nutrient Flux ▪ Carbon Flux	▪ Disturbance Regulation ▪ Prey Production ▪ Reproduction ▪ Refuge ▪ Carbon ▪ Sequestration ▪ Maintenance of Biodiveristy

While the need for more studies cannot be debated, there are predictions we can make about shoreline habitat modification being detrimental to those species associated with those habitats (Thom et al. 1994a). The general model and a hypothetical example are shown in Figure 5. In the example, an undisturbed fully functional shoreline habitat is modified by addition of a rock bulkhead. This human modification substantially alters the structure of the original habitat, increasing the original site elevation, changing the beach substrate composition from sand-gravel to hard rock, and removing riparian vegetation. In turn, habitat support processes are altered as sediment dynamics change, due to increased reflective wave energy and loss of sediment supply, and riparian shading is lost. Altered processes are reflected in changes to ecosystem functions, such as the loss of adequate beach spawning habitat for forage fish, which have specific elevation, sediment, and temperature requirements for successful egg hatching. Actions that can mitigate these impacts include avoidance (i.e., no bulkheading), minimization of impacts (use of alternative shoreline armoring strategies), and compensation (restoration of other degraded sites).

Habitats and Resource Linkages

Habitat structure in nearshore and estuarine habitats of Washington State largely correspond to locally prevalent physical processes, such as wave energy or substrate type (Dethier 1990) (Appendix A). An informed conceptual prediction of net changes or impacts to habitat structure may be made with knowledge of the physical processes being altered. In turn, the functional benefits of these habitats to fisheries and wildlife resources can be quantified using available literature summaries (Simenstad et al. 1991a) (Appendix B).

Expanding on the conceptual approach (Figure 3), the generic effects of shoreline modifications to marine species in Washington State can then be described based on:

- Physical changes caused by shoreline modifications, as identified in (Macdonald et al. 1994)
- Biophysical characterization of habitats, provided by Dethier (1990)
- The understanding of habitat-species linkages provided by Simenstad et al. (1991a)

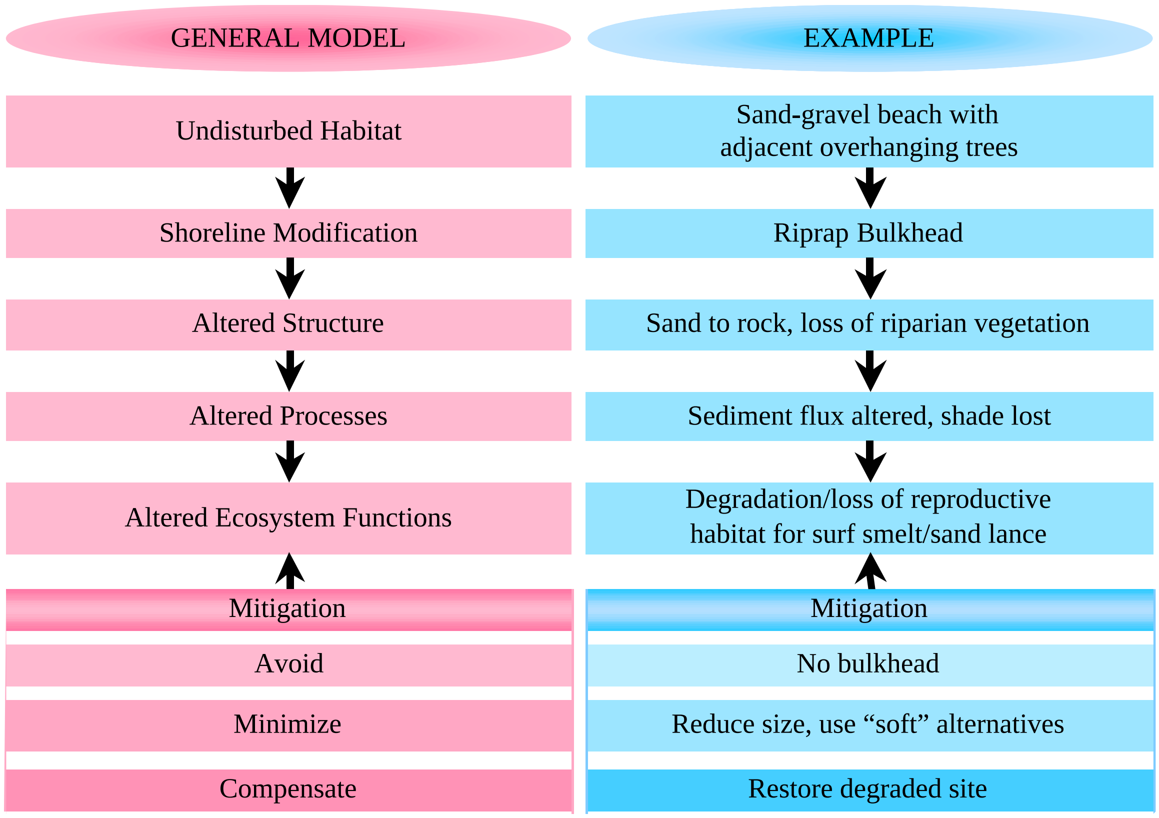

Figure 5. General conceptual model, with example, for evaluating effects of shoreline stabilization and restoration actions.

The primary mechanisms whereby shoreline modifications impact nearshore and estuarine fish and shellfish habitat use, include:

- Direct physical disturbance due to construction activities
- Geomorphology change
- Hydrology modification
- Water quality reduction
- Light level alteration

In the next section (Effects of Shoreline Modification), we use these mechanisms as a guide, to discuss how shoreline modifications may affect nearshore resources.

Effects of Shoreline Modification

In this section, we review the impacts of various shoreline modifications (Table 1) to nearshore and estuarine resources. First, construction and operation techniques are reviewed, with special consideration for regional approaches. A review of published studies, indexed by structure type, is then provided on biological responses to these shoreline modifications. We conclude with a discussion of documented physical effects and summary of likely impacts to local biological resources based on the conceptual model. It should be noted that although the broad range of shoreline modification activities has been broken down into several distinct categories for organizational purposes in this paper, many of these structures affect physical and biological resources in a similar manner (i.e., permanent loss or structural change of native habitats).

Energy Dissipating Structures: Breakwaters and Jetties

Breakwaters and jetties are constructed to dissipate wave energy, channel tidal action, and/or to protect and stabilize navigation channels and harbor areas. While both types of structures may serve widely different purposes, they are generally large landscape features that extend into subtidal habitats where they similarly affect physical processes and biological functions.

Construction and Operation Techniques

Breakwaters are self-supporting structures that offer protection to a backshore area, generally with the intent to dissipate wave energy and create calm water behind the structure (Mulvihill et al. 1980, U.S. Army Corps of Engineers 1984b). Breakwater designs can be fixed or floating, connected to shore or detached, segmented or continuous, and subtidal or emergent. Fixed breakwaters are built up from the sea floor and can be constructed from a wide variety of materials that possess the structural integrity to withstand constant wave action (e.g., rock, wood, concrete, metal, elastomeric materials). The most commonly used building materials are rough stone and precast concrete. Because their primary function is to reduce wave energy, most breakwaters are sited in high-energy environments where there is a long fetch or high incidence of wakes from vessel traffic. Placement is dictated by shore configuration and desired harbor design; consequently, most breakwaters are oriented parallel to the shoreline. Because wave deflection and absorption is a primary function of breakwaters, engineering design must take into account the physical environment (wave climate, bottom topography, tide, currents, substrate type) in which the structure is placed. Wave absorption function is affected by face slope, facing material, permeability, structure height, and water depth.

In Puget Sound most breakwaters are designed as walls or mounds, and are placed in water depths less than 4 m (Cox et al. 1994). Wall-type breakwaters are constructed of pile supported panels that allow navigation up to their edge, have a small footprint that minimizes damage to bottom habitat, and may be open near the bottom to allow circulation and fish passage. A disadvantage is that the facing wall of the structure does not absorb wave energy and can cause severe reflective wave conditions if sited improperly. Typical mound breakwaters in Puget

Sound are constructed of stone rubble or pre-formed concrete that extends about 0.6-m above maximum water level. Most are located less than 100 feet from the shore, and require periodic maintenance with sand or gravel fill (Cox et al. 1994).

Jetties are also self-supporting structures extending into the water to direct and confine river or tidal flow into a channel and to prevent or reduce shoaling of the channel by littoral material. Jetties are often located at one or both sides of coastal entrances to bays, harbors, or rivers, and usually intended to perform several functions, including stabilization of inlet location, direction of flow, reduction of channel shoaling from littoral drift material, and wave or current protection (Mulvihill et al. 1980). Jetties generally extend from above high water on the shoreline to below low water, which may extend into associated navigation channels or beyond the surf zone. Most jetties in the United States are constructed of stone rubble and prefabricated concrete; however, designs that are effective in preventing shoaling of navigation channels must be impermeable. Design and placement of jetties around inlets must take into account multiple hydraulic conditions (e.g., tidal prism, channel dimensions, storm-surge influence, wind-induced currents, wave effects), sediment dynamics, and navigation factors (U.S. Army Corps of Engineers 1984b). Training walls are comparable structures that perform similar functions with correspondingly similar impacts on the physical processes and biological functions.

Direct Studies of Biological Impacts

In Washington State, most directed research on the effect of breakwaters on biotic communities has occurred in the context of marinas, which include bulkheading and overwater structure elements (see Simenstad and Nightengale In Prep). Salmon fry and forage fish schools often concentrate in higher densities behind breakwaters in marina basins as compared to unaltered nearshore areas (Heiser and Finn Jr. 1970, Pentilla and Aguero 1978) (Table 8). Fish movement and schooling behavior in these studies suggested that concentration in these areas was volitional, and raised concerns by both authors about the extended effects of marina water quality on their health.

Heiser and Finn (1970) found that small (35-mm to 45-mm) pink and chum salmon (*O. keta*) fry were reluctant to leave the shoreline and venture along bulkheads or connected breakwaters until they reached a larger size (50-mm to 70-mm) (Table 8). These behaviors were attributed to higher observed rates of fry predation by coho smolts (*O. kisutch*) and cutthroat trout in deeper water. Bulkhead and breakwater design affected fry behavior, with steep vertical designs inhibiting migration potential, and natural material (e.g. riprap) with irregular surface configuration and low slope (<45 degree angle) providing more protective cover, shallow water shelter, and predation refuge. Culvert designs to provide passage were ineffective in this study, and the authors noted that tide level was an important consideration. No comparative estimates of residence time, growth, or survival were conducted to determine whether the sheltered breakwater/marina habitat afforded these species net benefits in terms of refuge and food. Unpublished papers have also documented shore-connected breakwaters in the lower Columbia River and coastal bays blocking fish movement along shallow water migration corridors and exposing salmon fry to increased predation (Stockley 1974 in Mulvihill et al. 1980).

Table 8. Shoreline Modification Impact: Response Matrix – Individual studies documenting responses of biota to particular shoreline modifications.

Shoreline Modifications:	Structural				Non-structural
	Energy Dissipating Structures	Shoreline Stabilization Methods		Other Structures Affecting Hydrology	Upland/Shoreline Management
Responses:	Breakwaters, Jetties	Hard Approaches: Bulkheads, Revetments, Seawalls, Groins, Ramps	Soft Approaches: Beach Nourishment (Sand and Gravel) and Biotechnical Measures (Vegetation, Large Woody Debris)	Tidegates, Outfalls, Artificial Reefs	Building Setbacks, Surface & Groundwater Management, Vegetation Management
Community Change: Burial or Removal of Resident Biota	Iannuzzi et al. 1996, U.S. Army Corps of Engineers 1984, U.S. Army Corps of Engineers 1981b	Jennings et al. 1999*, Li et al. 1984*, Knudson and Dilley 1987*, Gilmore and Trent 1974, Pentilla 1978, Ahn and Choi 1998	Simenstad et al. 1991a, Thom et al. 1994, National Research Council 1995, U.S. Army Corps of Engineers 1981f, U.S. Army Corps of Engineers 1981g, Antrim and Thom 1995, Parametrix 1985	Cheney et al. 1994, Cassidy and Guthrie 1982, Mearns et al. 1976, Packman 1977, Petrenko et al. 1997, Jones et al. 1996, Beamer and LaRock 1998, others	Smith 1997, Short and Burdick 1996, Meyers 1993
Habitat Complexity: Change in cover and preferred prey species	U.S. Army Corps of Engineers 1985	Ahn and Choi 1998, Jennings et al. 1999*, Li et al. 1984*, Knudson and Dilley 1987*, Weitcamp and Schadt 1982, Cardwell and Koons 1981, Gilmore and Trent 1974, Watts 1987, Engineering Science 1981, Toal 1993, Yoshinaka and Ellifrit 1974, Watts 1987, Moser et al. 1991*, Gregory and Levings 1996*	Simenstad et al. 1991a, Thom et al. 1994, Thompson and Cooke 1991, Parametrix 1985	Cheney et al. 1994, Mearns et al. 1976, Matthews 1989, Woodruff et al. 2000, Armstrong et al. 1980, U.S. Army Corps of Engineers 1980, Beamer and LaRock 1998	Smith 1997, Short and Burdick 1996, Meyers 1993, Manashe 1993, Zelo and Shipman 2000, Brennan and Culverwell In Prep., Pentilla 2000, Thom et al.1994, Levings et al. 1991
Behavioral Changes	Heiser and Finn 1970, Iannuzzi et al. 1996, U.S. Army Corps of Engineers 1985, Gregory and Levings 1996*, Pentilla and Aguero 1978, Mulvihill et al. 1980	Heiser and Finn 1970, Feist et al. 1996		Woodruff et al. 2000, Matthews 1989, Buckley 1997	
Predator Attraction	Heiser and Finn 1970, Iannuzzi et al. 1996, Pentilla and Aguero 1978, Gregory and Levings 1996*	Heiser and Finn 1970		Matthews 1989	

* denotes freshwater literature

Jetty and breakwater construction modifies the depth and availability of substrate attachment sites, thereby altering the composition of algae and other primary producers. One of the few studies to estimate rates of primary productivity change after breakwater construction and channel deepening estimated that microalgal and macroalgal nearshore productivity over bottom sediments in a Long Island embayment was reduced by 17% (Iannuzzi et al. 1996) (Table 8). However, anthropogenic structures resulted in a net increase in the relative availability of substrates for micro- and macroalgal colonization in the upper water column, a change that likely represented a significant deviation from the balance of sources contributing to primary productivity in the system.

In the Great Lakes, (U.S. Army Corps of Engineers 1985) rubble mound breakwaters constructed at a natural inlet for navigation and recreational access purposes resulted in short-term changes in water quality and temporary avoidance by fishes during construction (Table 8). Over the long term a diverse biological community developed on the hard structure, which provided foraging and spawning habitat for a variety of fish species.

The few published studies on the definitive impacts of jetties to the nearshore ecology were primarily descriptive USACE technical reports (Table 8). Construction of a weir jetty in South Carolina eliminated benthic communities directly in the path of jetty construction and disrupted infaunal communities adjacent to dredging areas and near the channel entrance (U.S. Army Corps of Engineers 1981j, U.S. Army Corps of Engineers 1984a). This was accompanied by the rapid development of attached floral and faunal communities on the introduced hard quarry stone substrates.

Physical Effects of Structure

The physical alterations caused by large, wave energy-dissipating structures such as jetties and breakwaters, dramatically alter the structure and functions of habitats at the site of direct impact, and effects may extend for a considerable distance beyond. The primary mechanism of these effects is manifested through chronic changes in regional hydrology, as well the direct impacts on structural aspects of the site. While these structures also have many of the same physical impacts of shoreline stabilization methods (see next section; e.g., permanent loss of habitat from placement waterward of ordinary high water, reflective turbulence, turbidity), we focus on hydrologic and subtidal impacts in this section to avoid unnecessary repetition within the document. We additionally consider these undocumented but likely indisputable effects to the biological impacts that have been documented in studies summarized above.

Breakwaters and jetties exert their most chronic impacts on nearshore hydrological processes, which include altered wave energy and current patterns, obstruction of littoral drift and longshore sediment transport, and altered fluctuations of temperature, salinity, and water levels. Most jetties are located at a river or bay mouth, where alteration of river outflow and tidal currents can affect flushing characteristics and tidal prism, with chronic widespread effects (including alteration of nutrient flux, sediment budgets, and physicochemical properties) that can be detected well upstream. Outside of an inlet, the most chronic effect of jetty placement is the alteration of littoral transport, which can impact bottom habitats, beach formation, and sand dune size. For example, prior to the construction of the Elliott Bay Marina in Elliott Bay, a divergent drift cell of about 0.5 mi in length was directed eastward along the riprap of Smith Cove, building an intertidal sand spit where the shoreline turns into Pier 91 (Schwartz et al. 1991). After the construction of the marina, a barrier to littoral drift was created, eliminating this small drift cell (H. Shipman, WA Dept of Ecology, personal communication, 20 Oct. 2000). Littoral transport may be facilitated by sand by-passing (pumping sand from the upstream to the downstream side of the jetty), although these actions are temporary in nature and may create bottom disturbance and turbidity.

Jetties and breakwaters may impede the movement of many species, including larval forms, through inlets and along shorelines via direct physical obstruction, current alteration, or physicochemical influences. They may also indirectly alter soft-bottom benthic communities in adjacent areas by altering patterns of sediment and organic matter transport.

Rubble-mound jetties and breakwaters radically alter the geomorphology of existing habitats, often resulting in a large-scale replacement of soft-bottom, deepwater habitat with shallow and intertidal, hard structure habitats. Hard-substrates provide settlement and attachment sites for a diverse assemblage of rocky shore organisms (Dethier 1990). Reef-like structures may also attract and concentrate fishes that are oriented to structure, depending on substrate composition, vertical relief profile, and sizes of interstitial spaces (West et al. 1994). These structures may also concentrate fish predators in critical migration corridors.

Direct physical disturbance associated with construction of all shoreline structures temporarily causes several types of direct impacts, which vary with the size and extent of the structure and the time needed to build it. In the short term, heavy equipment associated with construction causes local noise (e.g., pile driving), which can disrupt nesting waterfowl (Mulvihill et al. 1980) and alter animal behavior and distributions (Feist et al. 1996). Air and water pollution from machinery and watercraft exhaust emissions may also cause local impacts, and should remain well below federal air and water quality standards (Mulvihill et al. 1980, Kahler et al. 2000). Other construction impacts include temporary bottom disturbance, which increases sediment suspension, erosion, and turbidity. Juvenile and filter-feeding fish may be especially vulnerable to the lethal and sub-lethal effects of suspended sediments (O'Connor et al. 1976, O'Connor et al. 1977). Other obvious and immediate impacts associated with construction include burial or excavation of both subtidal and intertidal habitats and fauna, trampling, and direct mortality from heavy equipment operation (e.g., dredging (Armstrong et al. 1991)) or barge groundings. Construction impacts may continue episodically as maintenance activities continue, for example during channel dredging along jetties for navigation purposes.

Jetties and breakwaters may affect recognized functions of estuarine and nearshore habitats for juvenile salmon as follows:

- Migration—construction of the structure itself may inhibit or alter migration in situations where the structure is placed in a migratory pathway or exposes juveniles to predators in deepwater habitats; may create conditions that disrupt movement and concentrate individuals

- Nursery—can block or alter access through inlets to important estuarine nursery areas.

- Juvenile food production and feeding—can affect the production of prey by altering substrate conditions, water properties, and hydrologic conditions; can alter the flow of nutrients and detritus accumulation used by prey resources; may concentrate food resources; subtidal conversion/loss of habitat.

- Adult food production—may cover or hydrologically alter shallow vegetated and beach habitats used by spawning forage fish.

- Residence—could fragment nearshore landscape and alter habitat use and movement; may attract potential predators.

- Physiological transition—jetties at inlets may alter flushing characteristics, tidal prism, and physicochemical properties of estuarine habitats.

Shoreline Stabilization Methods

Shoreline erosion is a natural coastal process influenced primarily by wave energy, water level, landform, sediment properties, and currents (Downing 1983, Terich 1987). Shoreline stabilization methods involve the physical placement of structural elements along the shore and are often used in an attempt to limit or delay these erosional processes. Stabilization approaches can involve “hard” construction and armoring methods (e.g., bulkheads, seawalls, revetments, groins), soft methods such as beach nourishment or vegetation supplementation, or composite methods combining both hard and soft components (Cox et al. 1994). Nonstructural activities that involve local zoning or land-use regulations are covered in a later section on habitat protection and mitigation activities. Because most shoreline stabilization methods are designed to modify sedimentary processes, they directly impact biological resources most sensitive to these changes. Each shoreline stabilization alternative has its own suite of advantages and disadvantages not only to the property owner, but also to local beach conditions and the nearshore ecosystem (Table 9). In highly urbanized bays and estuaries, shorelines are often composed of a variety of these structures, which modify existing shorelines extensively to create space for deepwater berthing and navigation.

Table 9. Summary of the advantages and disadvantages of various shore protection alternatives (from Downing 1983).

Method of Erosion Control	Advantage to Property Owner					Disadvantage to Property Owner					Advantage to Beach / Ecosystem			Disadvantage to Beach / Ecosystem		
	Stops upland erosion	Improves scenic value	Low maintenance cost	Improves slope stability	Beach accretes rapidly	Does not stop erosion	Reduces scenic value	Requires maintenance	Subject to failure	Potential legal problems	Does not impede beach material supply	Does not destroy benthic habitat	Improves natural sand supply	Reduces supply of sand	Destroys benthic habitat	Promotes beach erosion seaward of structure
Bulkhead	X		X	X			X	X	X	X				X	X	X
Revetment	X		X	X			X	X	X	X				X	X	
Groin			X		X	X	X		X	X				X	X	
Construction setback		X	X	X		X					X	X				
Vegetation				X		X		X			X	X				
Beach nourishment	X	X		X	X			X			X		X		X	

Hard Approaches: Bulkheads, Revetments, Seawalls, Groins, Ramps

Construction and Operation Techniques

Bulkheads are vertical shoreline structures designed to prevent sliding or erosion of the land behind it, primarily by protecting it against waves and currents (U.S. Army Corps of Engineers 1984b). Functionally, bulkheads provide a vertical separation of land from water and are built to protect adjacent uplands from erosion, create shoreline real estate, and enable moorage of vessels adjacent to land (Mulvihill et al. 1980, U.S. Army Corps of Engineers 1984b). Similar structures that armor the shoreline to prevent landslides and to protect uplands from wave action include seawalls, which are self-supporting, and revetments, which are placed on or against an existing sloping embankment. Bulkheads are generally not used in areas exposed to severe wave action and may be used in concert with seawalls.

The durability, minimal space requirements, and low maintenance needs of bulkheads make them fairly attractive to the property owner (Table 9). However, they are also least in harmony with natural beach processes and are the most expensive of the structural alternatives for controlling erosion (Downing 1983). Consequently, bulkheads are more common in highly developed coastal areas. Depending on function, bulkheads are found in all tidal zones, ranging from the subtidal (e.g., boat mooring) to the terrestrial (e.g., erosion control). Important siting considerations for physical processes include height and location on the beach to prevent wave overtopping and backside erosion, base protection to prevent undermining due to toe scour, and structure slope and shape to minimize wave energy deflection.

Bulkheads are the most common shore protection technique used in Puget Sound (Downing 1983, Canning and Shipman 1995a). Predominant bulkhead designs in the region are vertically-oriented concrete, rock, or wood structures which are in direct contact with water action. (Downing 1983, Cox et al. 1994, Canning and Shipman 1995a) (Figure 6). Vertical, cast-in-place concrete bulkheads consist of a wide reinforced base, a cantilevered wall constructed with weep holes for drainage, coarse granular material for backfill, and riprap toe protection. For the most part, there are no engineering design criteria for vertically stacked rock walls. Most are built of oversized rock, backed with filter fabric and gravel embedded into the shoreline. Rock walls should not be stacked taller than 8 ft or intentionally placed in direct contact with water action (Cox et al. 1994). Wood is often used as a bulkhead construction material because it withstands impacts well, is more easily transported and assembled, and is easily repaired (Downing 1983). Additional lateral support is provided by tying the upper ends of the posts to "deadman" anchors embedded in the backfill.

A revetment is an armored slope built to protect existing shorelines or embankments against the erosive forces of current, wave action, or storms (Mulvihill et al. 1980, U.S. Army Corps of Engineers 1984b). Revetments generally parallel the contours of the shoreline and are commonly composed of riprap (randomly placed rock rubble), gabions (rectangular steel wire baskets filled with stones (U.S. Army Corps of Engineers 1984b), interlaced concrete forms, or grout- (concrete) filled bags (Downing 1983, Cox et al. 1994). Revetments are considered most suitable for protecting bank and bluff habitats in Puget Sound, and are relatively easy to construct and maintain (Cox et al. 1994) (Table 9). For example, extensive riprap is used to protect rail lines along much of the eastern shore of central Puget Sound north of Seattle. Design and siting considerations include beach composition, water levels, wave energy levels, frequency of damaging waves, seasonal changes in beach profile, slope, and beach use. Based on these considerations, revetment designs may vary the size, specific gravity, quality, and interlocking configuration of armor stones.

Revetments in Puget Sound typically extend from above the mean high water line to below the mean low water line (Canning and Shipman 1995a) (Figure 6). Protection of the base is necessary to prevent toe scouring because revetments rely on the internal stability of the beach upon which they rest. Consequently, the underlying supporting structures are often layered with a filtering material (filter cloth and gravel) to reduce scour. Quarry rock is usually placed on a prepared slope of 1-1/2:1 to 2, usually resulting in substantial beach fill (Downing 1983, Canning and Shipman 1995a). Revetments may interfere with water access or active recreation, and reflect wave energy offshore, causing scour in front of the structure. Alternative designs that improve shoreline access and aesthetics include berm revetments, that use a thick, mobile layer of cobble to dissipate wave energy and conform to the beach, and buried revetments composed of traditional stone material buried under a wave resistant gravel face (Cox et al. 1994).

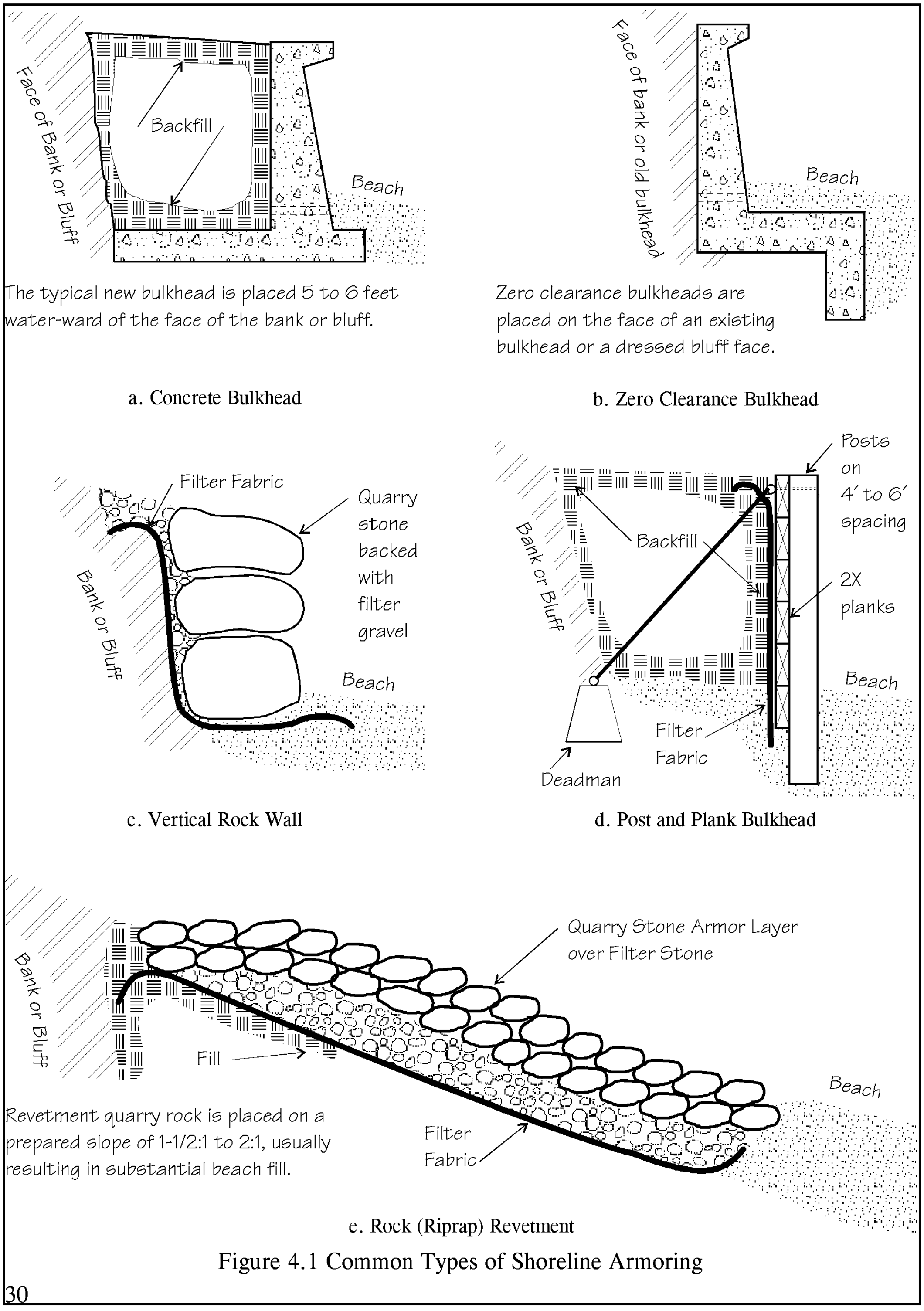

Figure 6. Common bulkhead and revetment designs in Puget Sound (Figure 4.1 from Canning and Shipman 1995a)

Seawalls are large freestanding structures designed to protect backshore areas from wave action by deflecting or dissipating wave energy (U.S. Army Corps of Engineers 1984b). In comparison to bulkheads, which are designed for shoreline protection in areas exposed to low waves, seawalls have a more three-dimensional form and are generally built to protect bluff and bank habitats exposed to moderate to very severe waves (U.S. Army Corps of Engineers 1984b). Seawalls may be constructed as rubble-mound or concrete structures, and rely on their own weight to maintain their position. They are generally composed of a foundation (a wide rock rubble base, supplemented with piles in areas with weak soils), toe protection to resist scour undermining (layers of large quarry stone and gravel), backfill protection to prevent erosion (pavement or quarry stone splash blanket), a splash apron at the crest, and features intended to redirect wave action.

In Puget Sound, typical seawall designs are cast-in-place concrete, with configurations that are step-faced to spread wave-loading time, or recurved to reduce overtopping with minimum structure height (Cox et al. 1994). Seawalls generally reflect wave energy, causing scour in areas adjacent to and immediately in front of the structure (Mulvihill et al. 1980); consequently, installation often includes supplemental armoring of foreshore and adjacent beach areas (Cox et al. 1994). However, more recent research disputes this single causal link (Kraus and McDougall 1996, U.S. Army Corps of Engineers 1992, U.S. Army Corps of Engineers 1995). Seawall construction costs may be considerably greater than most other shoreline protection methods because of scale issues, design complications, and the need to rework both the beach and adjacent upland to accommodate the structure.

A groin is a rigid, self-supporting structure built out at an angle from the shore (usually perpendicular) to protect it from erosion or to trap sand (U.S. Army Corps of Engineers 1984b). Groins may be designed to be permeable or impermeable to sediment. They commonly function to provide or maintain a beach by trapping littoral drift and reducing the rate of sediment loss, but can also be designed to prevent accretion by acting as a littoral barrier (Mulvihill et al. 1980). Groins are most commonly built on shallow sandy beaches; to function properly, they must be located in an area supplied by sand provided by littoral transport (Cox et al. 1994). They should also extend to the crest of the beach berm to avoid flanking by high wave action, and are typically spaced along the shoreline in what are referred to as "groin fields". Similar structures in freshwater systems are wing dams and spur dikes.

Groins, especially impermeable designs, are often constructed of sheet piles composed of wood and steel, although quarried stone, concrete, rubble, or asphalt are also common materials in Puget Sound. The design of a groin is highly affected by siting, and should reflect substrate type, material availability, and maintenance requirements. Likewise, groin height, spacing, and shape (straight, curved, and L-, Z-, or T-shaped) can also vary. Groin fields are generally considered ineffective for most of Puget Sound because there is not enough longshore transport to make them function properly (Downing 1983).

A ramp is a uniformly sloping platform, walkway, or driveway common in the coastal environment as a launching area for small watercraft (Mulvihill et al. 1980). Ramps extend into the water at a slope of 12% to 15% (Mulvihill et al. 1980) and are typically oriented perpendicular to the shoreline. The design of ramp widths (3m to 15 m) varies with patterns and intensity of human-use needs, whereas lengths often depend on the slope of the shoreline and tidal amplitudes. Ramps extend from the terrestrial zone to below the low intertidal zone and are usually constructed in protected areas with access to fairly deep water close to shore. Construction materials commonly consist of gravel, concrete, or asphalt; they are often associated with marinas and parking lots. In Puget Sound, boat ramps are commonly built for single family residential purposes. Elevated marine railways, which consist of a pair of railroad tracks supported by pilings extending from the upland down to the beach, are another common launching system in the region. Elevated concrete ramps or hybrid systems, that combine concrete ramps and marine railways, are two designs that protect sensitive forage fish spawning areas and minimize adverse impacts on habitat.

Direct Studies of Biological Impacts

One of the few studies to actually document fish behavior in the presence of bulkheads involved observations of salmon fry by small boat (Heiser and Finn Jr. 1970). Heiser and Finn (1970) found large concentrations of small (35-mm to 45-mm) pink and chum salmon (*O. keta*) fry in protected marinas. Salmon fry exhibited schooling and predator avoidance behaviors (reviewed in section on breakwaters, above) suggesting they were responding to bulkhead and breakwater structural design elements and were apparently reluctant to move into deeper water to go around the bulkhead (Table 8). The study recommended the use of breakwaters with a shallow angle of repose (45 degrees or less) instead of vertical walls. Although a fairly minor observational study, Heiser and Finn (1970) appears to have been influential in establishing subsequent shoreline stabilization design criteria for the region. It is included in most literature reviews documenting the effects of shoreline modifications on biological resources (Kahler et al. 2000, Mulvihill et al. 1980, Simenstad et al. 1991b, Thom et al. 1994a).

Construction activities associated with shoreline modifications that generate noise (e.g., pile-driving) may also affect the distribution and behavior of chum and pink salmon fry in Puget Sound (Feist et al. 1992) (Table 8).

Studies on the distribution and habitat requirements of forage fish spawning beaches have been similarly influential in assessing the impacts of hard shoreline stabilization methods (Toal 1993, Lemberg et al. 1997). The tidal distribution of forage fish spawning habitat is a function of tidal range, which varies by a factor of 3 times from north to south Puget Sound. Bulkheads within this tidal range destroy surf smelt (*Hypomesus pretiosus*) spawning beaches, alter the composition of adjacent substrate, and reduce egg survival due to loss of shading from riparian vegetation loss (Pentilla 1978, Pentilla 2000) (Table 8). Puget Sound clam populations are also negatively affected by bulkheads, with significantly lower abundance than in adjacent natural areas due to less favorable current patterns for larval settlement and survival (Yoshinaka and Ellifrit 1974).

A number of studies conducted along the East Coast (North Carolina, Chesapeake, New England) in the 1980's assessed the physical and biological impact of bulkheads on estuarine shorelines (Engineering Science 1981, Zabawa and Ostrom 1982, Watts 1987). In general, these studies demonstrated that bulkheads modified shoreline structure (vegetation and substrate) and were correlated to altered faunal assemblages. Bulkheads were shown to increase turbulence and wave scour that destroyed marsh vegetation channelward and prevented intertidal vegetation reestablishment (Engineering Science 1981, Watts 1987)(Table 8). The resultant habitat shift was reflected in lower concentrations of detritus, lower phytoplankton production, and fewer benthic organisms than adjacent unbulkheaded areas (Odum 1970 in (Watts 1987). Benthic macroinvertebrates and shrimp were more abundant, both numerically and volumetrically, along structurally complex natural estuarine shorelines than in simplified bulkheaded areas (Gilmore and Trent 1974, Mock 1966 in Watts 1987).

Weitkamp and Schadt (1982) compared migration timing and duration of juvenile salmonids moving or rearing along semi-natural shorelines and highly modified shorelines (piers and rip-rap) of the lower Duwamish Waterway and Elliott Bay (Table 8). Juvenile chinook were captured most frequently along natural shorelines with muddy sand, mud, and debris at lower intertidal levels; however, twice as many chum were caught at gently sloping rip-rapped mud habitats than natural areas with sandy gravel and compact sand.

Although few marine studies have compared the biological effects of rip-rapped stone revetments to natural shorelines, the freshwater literature does include some examples. Li et al. (1984) found that larval and juvenile fish densities and numbers of species were lower along continuous revetments as compared with natural banks; adult fish species richness was comparable, however (Table 8). They attributed these differences to the structural diversity of natural shorelines, which have a variety of habitats in terms of velocity, depth, and cover (Li et al. 1984). In a study of five pairs of streams in Western Washington, Knudsen and Dilley (1987) estimated that the numbers of juvenile coho salmon (*Oncorhynchus kisutch*), juvenile steelhead (*O. mykiss*), and cutthroat trout (*O. clarki*) were reduced by bank reinforcement activities. Negative effects of streambank modification on salmonids were apparently correlated with the severity of habitat alteration (positively), size of stream (negatively), and fish size (negatively) (Knudsen and Dilley 1987). Again, these effects were attributed to a reduction in habitat structural diversity.

Jennings et al. (1999) compared fish species richness associated with three different lakeshore habitat types: retaining walls, structurally complex rock riprap, and no structure (Table 8). They found that species richness was correlated with habitat complexity (rock riprap) and that the proportion of tolerant species changed in response to cumulative lakeshore effects. A number of other freshwater studies have found that both fish species richness and abundance were negatively correlated with bulkheads at every scale (see review by Kahler et al. 2000).

Based on their design similarities and functions, seawall impacts are likely similar to those of revetments and breakwaters. No studies documenting the biological impacts of seawalls in Washington State were found, although this may be related to the relative lack of this type of shoreline structure in the Puget Sound region. Ahn and Choi (1998) conducted one of the few quantitative comparisons of pre- vs. post-seawall construction impacts in Kyeonggi Bay Korea (Table 8). They documented altered hydrodynamic processes associated with seawall construction, which resulted in significant coarsening of substrates accompanied by shifts in the dominance of abundant benthic species (Ahn and Choi 1998).

Ramps and groins built from non-native material, such as concrete, result in permanent loss of habitat. In addition, if the ramp is above the natural beach grade, it will act as a groin and similarly affect the sediment transport system. We found no published literature on the direct impacts of groins or boat ramps to biota in the coastal zone. However, spur dikes (also known as groins) in the Willamette River appeared to be intermediate in habitat complexity and quality between natural banks and continuous revetments (Li et al. 1984) (Table 8). Spur dike-associated larval and juvenile fish densities and numbers of species were likewise intermediate between natural and fully-modified habitats (Li et al. 1984).

Physical Effects of Structure

Thom et al. (1994a) summarized the potential effects of shoreline armoring to selected nearshore resource species in Puget Sound based upon knowledge of critical links between physical effects, habitats, and biological resources (i.e., the conceptual model) (Table. 10). Examples of known physical effects and the likely resource impacts are discussed in further detail throughout the rest of this section.

Table 10. Summary of armoring effects to resource species in Puget Sound (from Thom et al. 1994a).

	Armoring Effects [a]						
Resource Species	Armoring-related Habitat Shift	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	●		●	●	●	●	●
Pacific Herring	⊕	⊕					
Hardshell Clams	●	⊕				●	
Geoduck	○						
Oysters	○	○				○	
Dungeness Crab	⊕	⊕				⊕	
Sea Cucumber	○					○	
Sea Urchins	○					○	

[a] Filled circles represent well documented evidence of negative effects, cross-filled circles represent high potential for negative effects but not documented, and open circles indicate some potential for longterm effects but not documented.

The placement of hardened structures along natural shorelines can influence erosion processes that alter the structure and function of native habitats at areas both near and distant from the site of impact. This effect appears to be consistent throughout protected bay and estuarine habitats, as well as outer coast environments. For example, in a field survey of the entire developed ocean coasts of South Carolina, North Carolina, and New Jersey, Pilkey and Wright (1988) showed that dry beach width was significantly narrower in front of stabilized seawalls and that areas with a higher degree of stabilization correlated to narrower beaches. Limited quantitative understanding of interactions between shoreline processes and hardening structures continues to fuel an ongoing debate over the cumulative effects of shoreline armoring on beaches and adjacent properties (Krause 1987, Pilkey and Wright 1988). However, the preponderance of evidence suggests that biological communities do respond to physical changes on a localized level.

Possibly the most significant effect of hardened shoreline stabilization is a direct impact to regional geomorphology via the impoundment of potential natural sediment sources (Macdonald et al. 1994). Structures located above the natural beach grade can cut off sediment supply from a feeder bluff or upper beach and will cause direct onsite impacts to habitat structure (e.g., shift to a lower elevation, higher energy, hard substrate shoreline), as well as indirect impacts within the coastal drift cell (Downing 1983). Shoreline structures designed to affect shoreline sediment transport (e.g., groins) will cause similar beach erosion and accretion impacts in adjacent areas (Pilkey and Wright 1988). Even structures built above the ordinary high-water mark may affect important natural physical processes that occur during unusually high wave or storm events. Changes in the physical composition and volume of substrates have predictable affects on biological resources (Macdonald et al. 1994, Dethier 1990, Thom et al. 1994a). Long-term, chronic impacts may result in a reduction of intertidal habitat area, bottom complexity, and associated soft-bottom plant and animal communities.

Structural modifications may directly alter shoreline geomorphology, which includes tidal elevation relative to MLLW, gradient, channel characteristics (depth, width, cross-sectional area, sinuosity), and sediment character and quality. Geomorphology affects rates of tidal inundation and exchange, and is responsible for most of the distinguishing physical and chemical features of tidal systems. Placement of structures below the ordinary high water mark often affects a permanent loss of habitat, reducing the availability and extent of intertidal foraging, spawning, and refuge areas.

Hardened shorelines with vertical or recurved slopes alter hydrology by deflecting wave energy downward, causing scouring of the bottom sediment at the toe and periphery (Engineering Science 1981, Zabawa and Ostrom 1982). This ultimately results in elevation loss and habitat change (Figure 7). Added turbulence and scour may prohibit vegetation establishment and alter the floral assemblage (Watts 1987, Thom et al. in prep). Loss of sediment supply can lead to erosion of beach profiles and lowering of the beach gradient. This change will result in loss or impairment of species and communities adapted for utilizing higher elevations and particular substrates.

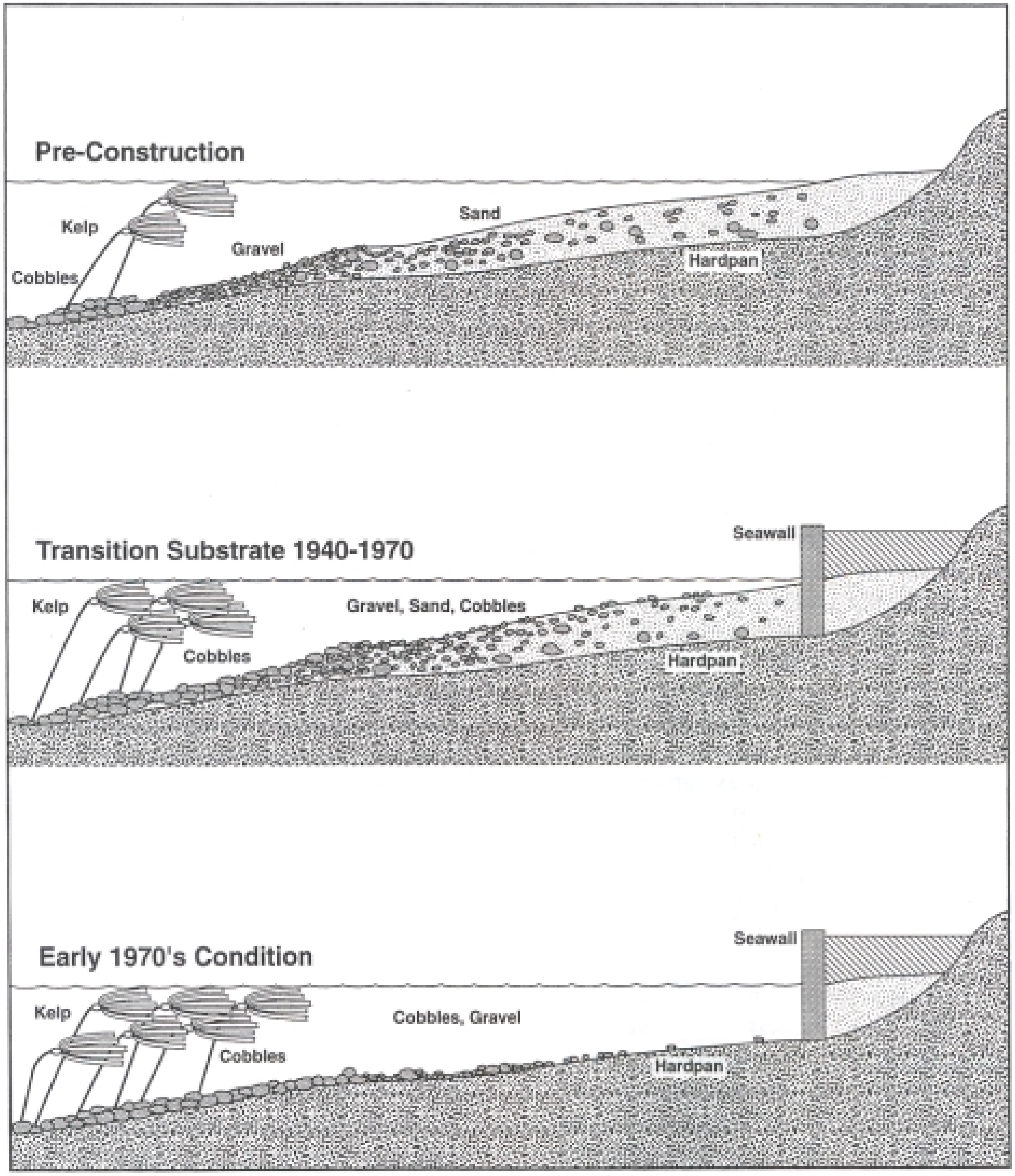

Figure 7. Illustration of changes in the beach at Lincoln Park following seawall construction in the mid 1930s (from Thom et al. 1994a).

The placement of shoreline structures waterward of the ordinary high water (OHW) mark can also result in the permanent loss of habitat for a number of species (Macdonald et al. 1994, Thom et al. 1994a). One of the more widely recognized biological impacts is the direct loss of fish (e.g., surf smelt, Pacific sand lance, and rock sole (*Lepidopsetta bilineata*)) spawning habitat on upper intertidal beaches (Thom et al. 1994a). Exacerbating these direct impacts is the indirect loss of additional spawning habitat from downdrift beach coarsening and erosion, and the loss of shading riparian vegetation (Macdonald et al. 1994, Thom et al. 1994a, Macdonald 1995, Antrim et al. 1995, Pentilla 1996).

Alterations to nearshore hydrology affect local sediment conditions, which can affect habitat structure. Changes can be manifested as loss or increase in sediment supply to an area, or altered flow rates which change the sediment grain size, which can be important to the types and number of plants and animals found in an area. For example, increased erosion of adjacent shorelines and littoral drift alteration modifies food and cover for transient and resident species, thereby reducing diversity and densities of locally adapted populations. In addition, organic matter content can change with altered sediment grain size. Organic content provides food for small animals residing in the sediment, as well as a source for remineralized nutrients important to support growth of rooted plants. Finally, larger woody debris (e.g., logs) which support both the development of microhabitats (e.g., pocket marshes, sheltered dunes) high on a beach and can stabilize beaches, may be effectively eliminated from an area.

Where hydraulic modifications cause alterations in the delivery of water to a nearshore area, the delivery of dissolved inorganic nutrients (e.g., nitrate, phosphate) may be altered also. For example, dikes placed around tidal wetlands alter the flow of both nutrients and sediment into and out of the wetland. This affects the ability of the system to accrete sediment (i.e., build elevation) as well as provide nutrients required by plants. Although not well studied, groundwater may be a source of nutrients to Puget Sound and other aquatic systems in the state. Interruption or alteration of the rates and patterns of groundwater exchange may also reduce groundwater supplies.

Water quality may degrade in areas of extensive shoreline modifications. Residential and commercial development and impervious surfaces in upland habitats and watersheds can increase stormwater runoff, sediment erosion, and loading of nutrients and toxic pollutants. Increases in shoreline development from housing can increase local nutrient loading to the point of eutrophication (Short and Burdick 1996). Removal of vegetative buffers may exacerbate these problems. Increased turbidity levels from sediments suspended by added turbulence and scour may also affect vulnerable juvenile and filter-feeding fish (O'Connor et al. 1976, O'Connor et al. 1977).

Shoreline modifications usually involve riparian vegetation removal, which displaces trees and shrubs that normally overhang onto beaches. A substantial mass of allochthonous leaf material can enter the marine system and be transported offshore during extreme high tides (Thom and Albright 1990). While presently not well studied, the role of leaf litter and insect fall from this riparian vegetation is likely important in nearshore detritus production and food webs. For example, insects produced in the riparian zone have been found in the stomachs of outmigrating juvenile salmonids (Miller and Simenstad 1997, Simenstad and Cordell 2000). Loss of woody debris also reduces shallow protective cover and nutrients.

Light levels in nearshore habitats are increased when anthropogenic shoreline alterations remove overhanging riparian vegetation, which provides shade that regulates heating of the upper intertidal zone. Shade reduces mortality and desiccation stress to insects, marine invertebrates, as well as to fish eggs laid by intertidal spawning fish species, including sand lance and surf smelt (Pentilla 1996, Pentilla 2000). Likewise, the increase in artificial lighting that often accompanies anthropogenic shoreline alterations can modify fish behavior and predator avoidance (Simenstad et al. 1999, Azuma and Iwata 1994). Conversely, shading by anthropogenic shoreline alterations may also unnaturally reduce local light levels, reducing primary productivity rates and eliminating critical shallow water vegetated habitats.

Shoreline stabilization activities that increase human use and accessibility (e.g., boat ramps) may cause sediment disruption, boat wakes, petrochemical pollution, and human disturbance.

Shoreline armoring may affect the recognized functions of estuarine and nearshore habitats for juvenile salmon as follows:

- Migration—construction of the structure itself may inhibit or alter migration pathways; loss or simplification of intertidal habitat exposes juveniles to predators in deepwater habitats; scouring may result in loss of sheltered eelgrass migration corridors in nearshore habitats.

- Nursery—alteration of sediment supply and riparian vegetation (e.g., LWD) can cause habitat shifts, loss of eelgrass, and simplified habitat structure, thereby reducing sheltered nearshore nursery areas.

- Juvenile food production and feeding—changed wave energy regimes can affect the production of prey by altering substrate conditions, water properties, and hydrologic conditions; can alter the flow of nutrients and detritus accumulation used by prey resources.

- Adult food production—may cover, hydrologically alter, or change critical sediment properties, or remove shallow vegetated and beach habitats used by spawning forage fish,

- Residence—could fragment nearshore landscape and alter habitat use and movement, may attract potential predators and/or reduce habitat complexity and cover.

- Physiological transition—cumulative impacts to shoreline habitats within a particular watershed (e.g. Duwamish waterway) may reduce areas for physiological transition.

Soft Approaches: Beach Nourishment and Biotechnical Measures

Soft approaches to shoreline modification involve natural materials that can deform and adjust over time to changing shoreline conditions (Cox et al. 1994). These methods strive to create minimal impacts to nearshore habitats and are considered a preferred approach to rebuilding or stabilizing shorelines (Table 9).

Construction and Operation Techniques

Because beaches and shorelines are dynamic, constantly eroding and accreting in the face of waves, currents, and wind, sediment nourishment is one strategy used to preserve shorelines and satisfy various socioeconomic needs. Beach nourishment serves as a “soft”, sacrificial barrier that functions to prevent beach recession, provide protection from storms and flooding damage, and enhance recreational opportunities (U.S. Army Corps of Engineers 1984b). Additional advantages include the preservation of beach aesthetic values and an increased supply of sediment to downdrift beaches.

Beach nourishment has been commonly employed on sandy, open ocean shorelines to extend a beach and the nearshore shallows seaward (e.g., southern California, East Coast barrier islands) (National Research Council 1995). However, beach nourishment on Puget Sound typically involves the use of coarse gravel to combat shoreline erosion at relatively small sites (Downing 1983, Cox et al. 1994, Shipman 1998, Shipman et al. 2000, Zelo and Shipman 2000). Both nourishment systems involve the borrowing of fill material, the transportation of this material, and its placement, often in integration with hard structures (e.g., groins and jetties, see above). Borrow material for beach nourishment may occur from offshore deposits, although much of the sediment nourishment in Puget Sound utilizes land-based sites.

The most important borrow characteristic is sediment grain size, which should closely match the coarseness of native material, contain no contaminants, and have low silt and clay fractions to avoid turbidity problems (National Research Council 1995, U.S. Army Corps of Engineers 1981g). Fill transport at coastal sites is generally accomplished by cutter-suction or hopper dredges, which pump the borrow material directly to the beach fill site via pipelines. Sediment placement can occur directly on the beach (e.g. as dunes or along the beach profile), immediately seaward of the beach (e.g., as a bar), or in some combination thereof.

Beach nourishment in Puget Sound typically uses gravel-sized material, placed by truck or barge along the upper beach, and spread to the design contour by bulldozer (Shipman 1998). Some beach nourishment projects in Puget Sound specify the use of clean round pea gravel, as opposed to crushed rock, with 80% of the material between 1.5 to 6.3 mm diameter. Most projects in the region involve 5-10 cubic yards of material per linear foot of shoreline, and attempt to imitate the natural profile of beaches in the general area. Gravel mixes are also recommended for filling pits and depressions in muddy areas when they are disturbed, and especially holes remaining after treated wood piling are removed. Coarse fill material may be more economical because of its erosion resistance, but may also incur costs due to loss of recreational and biological functions

(Downing 1983). Dominant processes relevant to the performance of the fill placement are alongshore spreading rates, water levels, beach profile, and the presence of terminal retaining structures (e.g., natural headlands). Placement design should include estimates of wave height and direction, cross-shore and alongshore transport rates, and sediment grain size. Nourishment does not address the underlying cause of erosion and should be undertaken with an ongoing commitment for periodic maintenance (Shipman 1998). Gravel placement is also used in Washington State to enhance bivalve production (Simenstad et al. 1991c), restore surf smelt spawning beds after bulkhead construction (B. Taylor, personal communication), and provide habitat for juvenile salmon epibenthic prey organisms (Parametrix, Inc. 1985).

Vegetation and other biotechnical approaches can be used to reduce soil erosion and increase slope stability along shorelines (Myers 1993, Manashe 1993, Macdonald et al. 1994). Along sloping shorelines and dunes, this approach involves the planting of vegetation in critical areas in order to harness the hydrological and mechanical benefits of plant foliage and root systems to stabilize soil characteristics. The hydrologic mechanisms responsible for these benefits involve rainfall interception and moisture depletion, while mechanical mechanisms (predominantly roots) assist in soil reinforcement, anchoring, weight surcharge, and particle binding (Myers 1993).

In marshes, the aerial portion of herbaceous plants dissipates wave energy and reduces sediment transport, while the dense root-rhizome mat adds stability to shore sediments (Knutson and Woodhouse Jr. 1983). In shoreline or marsh habitats, soil type and grain size, oxygen aeration, nutrient levels, salinity, exposure to sunlight, shore width, sediment supply, and wave climate should be assessed (Knutson and Woodhouse Jr. 1983). For successful establishment and growth of marsh vegetation in Puget Sound, local stocks of native species should be planted that match prevailing site conditions (Weinmann et al. 1984). The protection of upland portions of sandy shorelines can be accomplished through native plantings (e.g., American dunegrass - *Elymus mollis*) that stabilize or initiate the creation of barrier dunes (Downing 1983, Cox et al. 1994).

In upland habitats, site evaluation should include an assessment of slope angle and height, soil type and condition, microclimate, drainage, existing vegetation, and probable erosive forces (Myers 1993). Slopes should be separated into three areas: the crest, face, and toe, with addition of native plantings appropriate to each zone. Planting techniques can involve seeding, live staking, and container or bare root plantings of native species that can be used in combination with other slope stabilization designs, such as brush layering or contour wattling (Myers 1993, Levings 1991).

Large woody debris (LWD) (stumps, drift logs, tree root masses) is a natural component of Pacific Northwest shorelines and beaches and can function to trap sediment and absorb wave energy (Zelo and Shipman 2000). Drift logs form semi-permanent stockpiles which trap beach sediment and promote the establishment of vegetation on beaches with large berms (Downing 1983). Natural protection of shore bluffs may be provided by drift logs in this manner along many undeveloped beaches in Puget Sound. Some beach protection and shoreline restoration efforts utilize LWD to harness these functions and provide a natural alternative to conventional manmade structures. Installation of LWD involves anchoring the material with steel cables to imbedded earth anchors (typically precast concrete blocks or screw anchors) (Zelo and Shipman 2000). Under extreme conditions, however, anchored wood may become unstable and cause damage to property.

Direct Studies of Biological Impacts

In most high-energy coastal beach environments wherein beach nourishment is conducted, studies have shown that highly mobile fauna are adapted to heavy disturbance regimes and recolonize these areas quickly (U.S. Army Corps of Engineers 1981f, National Research Council 1995) (Table 8). However, in some cases the recovery rate of macrofauna in offshore borrow pits may be slow and depends on local physical and chemical conditions (U.S. Army Corps of Engineers 1981f). Fine sediments transported during storm events may also bury populations of less mobile fauna located offshore (U.S. Army Corps of Engineers 1981g).

At Lincoln Park in West Seattle, beach nourishment was initiated to restore historic intertidal soft bottom habitat after a constructed seawall limited sediment supplies and increased wave energies on the site (Antrim and Thom 1995). Additional expected benefits of the sediment included protection of shoreline, eelgrass restoration, and increased cover and prey for juvenile salmon. Monitoring showed that the added sediments resulted in an expected change of the beach substrata from hardpan and cobble to course sand and gravel. Bivalve populations were reduced substantially and hard bottom sites used for bull kelp attachment were covered (Antrim and Thom 1995) (Table 8).

Specific studies on the impacts of beach graveling have shown that burial of existing sediments and modification of substrate size and structural complexity can lead to shifts in benthic assemblage composition (Thom et al. 1994b) (Table 8). Enhanced secondary productivity in graveled areas has been documented by increased clam production (Thompson and Cooke 1991, Simenstad et al. 1991c) and standing stocks of some epibenthic prey resources for juvenile salmon (Simenstad et al. 1991c).

Sand and gravel "blankets" have also been used as a mitigation approach to supplement habitat for epibenthic crustaceans (juvenile salmonid prey) in riprap under pier aprons for the Ports of Seattle and Tacoma. In a study by Parametrix Inc. (1985), the density and diversity of epibenthic organisms was influenced by tidal elevation, substrate composition, and sample timing (Table 8). Average densities were higher at lower elevations and within fine, sandy substrates (especially for harpacticoid copepods). A wider variety of particle sizes and substrate types produced higher community diversity. Consequently, the highest average epibenthic organism densities were found at the sand control site, the lowest within the riprap control site, and intermediate levels (depending on tidal height and substrate type) were found at the sand/gravel blanket treatment sites. However, gravel was a more stable blanket material and was retained better by the large riprap, whereas sand sloughed down the slope readily.

Few studies have documented the impacts of riparian vegetation restoration on marine systems, although the vital functions of these critical habitats are becoming recognized and most restoration actions are considered be beneficial (Brennan and Culverwell in prep, Levings 1991). Likewise, no systematic study has examined the use of wood in restoration or erosion control projects on marine shorelines, or the expected benefits these natural shoreline components accrue as habitat to nearshore species (Zelo and Shipman 2000).

Physical Effects of Structure

Soft approaches to shoreline stabilization strive to create minimal impacts to nearshore habitats and are considered a preferred approach to rebuilding or stabilizing shorelines. Although construction impacts in the near term cause direct impacts, chronic or indirect impacts of soft approaches are considerably less than those caused by hard structures (Downing 1983) (Table 9).

Depending on placement design, short term beach nourishment impacts may occur on or in the littoral, intertidal, and the subtidal zones, and include burial, activity disruption (foraging, breeding, nesting), increased turbidity, and changes in wave action and bathymetry (National Research Council 1995). Nourishment of a shoreline with substrate not well matched to native sand/gravel size and heterogeneity may also negatively impact biological functions. From a physical perspective, use of coarse gravel may be a more economical choice because its erosion resistance reduces replenishment frequency, although the literature does not definitively indicate the relative success or failure of pea gravel in beach nourishment projects. In some cases, relatively homogeneous gravel mixtures may provide few of the intended ecological benefits in some intertidal habitats, resulting in steepened beach slopes (Downing 1983), little moisture retention when drained, and instability under minor wave action. Under these conditions, coarse pea gravel material may not support infauna or epibiota, primary production, or appropriate surf smelt spawning habitat (J. Houghton, personal communication).

Riparian vegetation is a key element of shoreline ecological function and has a significant influence on habitat value, both in the riparian zone itself, and in adjacent aquatic and terrestrial areas (Zelo and Shipman 2000). Marine riparian zones serve many of the same beneficial functions as freshwater systems (Gregory et al. 1991, Naiman et al. 1992), while likely providing additional functions unique to nearshore systems (Brennan and Culverwell in prep). For example, Brennan and Culverwell (in prep) identified 205 wildlife species (5 amphibians; 4 reptiles; 153 birds; and 43 mammals) in a review of wildlife species known, or expected to have a direct association with riparian habitat along the marine shores of Puget Sound.

Dune grass and berm vegetation can greatly increase the resilience of beaches to storm waves (Zelo and Shipman 2000). Large woody debris (LWD; snags, stumps, driftwood) are a distinctive and significant feature of Pacific Northwest coastlines and beaches that help to retain sediments and absorb wave energy, and can be incorporated into alternative bank protection strategies (Zelo and Shipman 2000, Macdonald et al. 1994).

Soft approaches to shoreline stabilization may affect the recognized functions of estuarine and nearshore habitats for juvenile salmon as follows:

- Migration—project construction may inhibit or alter migration pathways and feeding patterns in the short term; restoration of intertidal substrate may allow recolonization of sheltered eelgrass migration corridors in nearshore habitats.

- Nursery—restoration of sediment supply and riparian vegetation (e.g., LWD) can result in increase habitat structural complexity and sheltered nearshore nursery areas.

- Juvenile food production and feeding—restoration of substrate conditions appropriate for preferred epibenthic prey items, may enhance detritus accumulation used by prey resources, insect fall from riparian vegetation may enhance feeding opportunities.

- Adult food production—may restore critical sediment properties or increase shallow vegetated substrates used by spawning forage fish.

- Residence—LWD and riparian vegetation will enhance refuge conditions and residence time for some species (e.g., sea-run cutthroat trout).

- Physiological transition—beach nourishment may restore backshore and spit habitats near river mouths, enhancing shallow estuarine areas for physiological transition.

Other Structures Affecting Hydrology: Tide Gates, Outfalls, and Artificial Reefs

Construction and Operation Techniques

Tide gates, or flap gates, are flow-control devices that function as check valves in diked tidal systems, allowing unidirectional water flow from a stream into an estuary or river. They are typically attached to culverts placed through dikes and allow normal drainage of stream flow while preventing high tides from backing saline water into the stream channel (Bates 1997). Tide gates usually consist of a flat plate that is hinged at the top of the culvert outfall and falls vertically over the face of the culvert opening. A positive force against the downstream face of the plate forces it open to release water, while a positive force against the upstream face seals it closed against the culvert opening. Other designs include manually operated, latched tide gates that can be closed during flooding emergencies but remain open at other times of the year for fish passage and maintenance of estuarine conditions upstream. Tide gates are typically constructed of cast iron, but may also be made of plastic, fiberglass, aluminum, or wood. Lighter materials are beneficial because gap openings can be maximized under lower flow rates.

Outfalls

Waste Discharge

Waste discharge outfalls that discharge into marine waters are generally cylindrical pipes that are constructed of reinforced concrete or metal. Outfall lines often are oriented perpendicular to the water line, with discharge points into marine waters ranging from very high on a beach to deep subtidal. For example, the wastewater discharge outfall pipe of Duwamish Head discharges at approximately 600ft, making it the deepest outfall on the West Coast of the United States.

During construction, burial of the pipes requires excavation of sediment, which is typically stockpiled on a barge and used to backfill on top of the pipe once it is in place. Intertidal discharges are common in Washington, and these may be simple pipes or larger culvert-like structures with a reinforced face at the seaward end. For subtidal outfalls, the end of the pipe may contain a diffuser (i.e., a section of pipe with several holes or ducts) which is meant to diffuse the wastewater as it flows out of the pipe. The end of the line may be anchored to the bottom using larger concrete footings. To be most effective, outfalls are sited in areas with enhanced current speeds to help flush and dilute the discharge.

Stormwater Outfalls

Stormwater outfalls, which drain municipal streets and storm drains, are much more common than wastewater outfalls in Puget Sound. These may emanate from a single source such as a single family residence to large combined sewers handling runoff as well as sewage. Stormwater outfalls range from small flexible hoses draped over a bluff to those resembling sanitary sewer pipes and outfalls. Construction of large stormwater outfalls incurs the same type of impacts as those associated with wastewater outfalls, including excavation of sediment, and back filling of the outfall trench. The simplest outfall, type, the hose, is simply lain over the surface of the land and is allowed to drain into a receiving water body or onto adjacent land. The characteristic of stormwater outfalls is that flow is highly variable, with greatest flows occurring during rainy periods. Most stormwater outfalls have no controls on them. Combined sewer overflow outfalls, such as those used in Seattle, transport sewage as well as street runoff to the wastewater treatment plant during most periods. However, when flow volumes exceed treatment plant capacity, the combined wastewater is discharged directly into Puget Sound. Stormwater flows can erode soils and sediments at for some distance beyond the discharge point.

Artificial Reefs

Artificial reefs have been used to attract fish and invertebrates for decades and longer, and have been used to enhance recreational diving and fishing opportunities worldwide. Some of the earliest quantification of the benefits of reefs was conducted in southern California (Turner et al. 1969). A wide number of materials have been used to construct artificial reefs (Grove et al. 1991, Sheehy and Vik 1989). Table 11 lists the types and goals of various reef types in estuaries.

Table 11. Materials used in artificial reefs in estuaries (Grove et al. 1991)

Material and Structure	Application
Natural Materials	
Oyster shell	Habitat enhancement
Quarry rock	Recreational fishing
Stone	Habitat enhancement
Wooden frames	Recreational fishing
Manufactured or Scrap Products	
Poured concrete	Recreational fishing, Habitat enhancement, Experiment
Concrete Rubble	Recreational fishing
Midwater buoys	Recreational fishing, Habitat enhancement
Automobile tires	Recreational fishing, Habitat enhancement
Automobile bodies	Recreational fishing, Habitat enhancement
Steel vessels	Recreational fishing

Materials are generally offloaded from a barge or boat and either placed by hand or by crane into position. Artificial reefs can range greatly in size, from a meter in diameter to greater than one hectare. Consideration should be given to structure slope to maximize reef quality, and that substrate size is large enough to be stable under wave action (U.S. Army Corps of Engineers 1980).

Reefs in Washington State have been constructed of a wide variety of materials, with rock and concrete being the primary materials of choice. At Edmonds Underwater Park, materials have included natural materials, plastic, and steel. An artificial reef near Blake Island was constructed of concrete rubble, slabs, rectangular boxes and tires (Matthews 1989). Artificial reefs constructed with scrap concrete and quarry rock materials at Boeing Creek and Gedney Island have been extensively studied by Buckley (1997). Contiguous reef substrate cover 6,000 m^2 and 1,665 m^2 at Boeing Creek and Gedney Island, respectively. Pit run aggregate (10- to 20-cm diameter) has been used in Elliott Bay to create a rocky beach (2-ha) and subtidal area (3-ha) to mitigate loss of shallow water feeding habitat for juvenile salmon (Cheney et al. 1994).

Although oyster reefs have not been constructed in Puget Sound similar to those in the Chesapeake Bay (e.g., Coen and Luckenbach 2000), shell placement has also been used to enhance the abundance and survival of Dungeness crab in Washington outer coastal estuaries (Armstrong et al. 1991). Oyster shell is deposited off barges onto natural intertidal or shallow subtidal bottom. The shell piles, which can reach on the order of 0.75m in height when first deposited, create a complex matrix of protective, food-rich habitat for newly settled crab. The shell covers natural bottom, which can include eelgrass and mud flats. Through time, the shell disappears through burial or sinking, making renourishment necessary.

Physical Effects of Structure

The physical alterations caused by tide gates, outfalls of various types and sizes, and artificial reefs result in damage to both the structure and functions of habitats at the site of the direct impact as well as distant from the site of impact. The mechanism of effect is manifested through changes both in the controlling factors as well as the direct impact on structural aspects of the site. To the impacts that have been documented above, we add these undocumented but likely indisputable effects.

Tide gates

Tide gates alter hydrology, physical connections between habitats (e.g., the marsh and the estuarine system), sedimentation processes, water quality, and organic matter flow. Hydrological alteration can result in increased water temperature, altered dissolved oxygen, and altered concentrations of some chemicals. Because water can stagnate while behind the dike, oxygen is depleted and anaerobic processes responsible for increases in hydrogen sulfide concentrations and methane production can be enhanced in organic soils. The pulse of water released can be have a much lower dissolved oxygen concentration as well as have increased water temperatures (in spring and summer), and enhance concentrations of sulfides. Each of these alterations are known to be potentially stressful or toxic to estuarine animals. Because the water that builds up behind a tide gate is usually fresh, the pulse of water released is substantially lower in salinity than the receiving waters. The restriction by the tide gate prevents the natural mixing of salt and freshwater within the diked former tidal wetland. In addition, the organic matter flows between the estuary and the diked system are restricted to one-way. Hence, organic mater produced in the estuary cannot reach the diked wetland. Finally, sedimentation is reduced substantially within the diked system. Tidal marshes depend on the natural sedimentation process as part of the natural marsh accretion process. It is estimated that about one-half of the accretion in the Pacific Northwest tidal marshes is from sediments (Thom 1992). Without natural accretion, marshes succumb to rising sea levels. Although dikes are the primary reason why estuarine-dependent juvenile salmon cannot reach rich feeding habitats in marsh channels, poorly designed tide gates may allow limited access to the sites. Access would be dependent on the flow rates through the gate, with high flow rates preventing small fish from accessing critical marsh and freshwater habitats. Because of the very restricted size of most tide gates, trapping of fish behind the gate is also potentially a problem. Reduced water quality (as mentioned above) along with increased availability to avian and fish predators may be enhanced in these restricted tidal channels within the diked system.

Tide gates may affect the six functions of estuaries for juvenile salmon as follows:

- Migration—tide gates may inhibit migration in situations where the tide gate is placed in the migratory pathway such as across a stream that enters en estuary.
- Nursery—tide gates can block access to important nursery areas.

- Juvenile food production and feeding—tide gates can affect the production of prey because of altered water properties and wetland conditions, alter access to areas of prey production, and alter the flow of prey resources to the location where they can be utilized by the fish.

- Adult food production—the production of small fish, which may be a portion of the diet of adult salmon, might be limited by loss of rearing and feeding habitat for these fish.

- Residence—tide gates could block the normal patterns of use of the tidal systems, especially tidal creeks in marshes, thus reducing the period of residence.

- Physiological transition—fish trapped behind a tide gate may be subjected to highly altered salinity regimes which may affect physiological transition processes.

Outfalls

There are myriad impacts from sewage and stormwater discharges on the marine and estuarine environment that are not addressed in this paper. In general, these discharges result in decreased salinity, altered temperatures, altered water clarity, increased inorganic nutrients (e.g., ammonia), increased organic matter loading, and increased levels of biological contaminants such as coliform bacteria, viruses, as well as chemical toxicants (e.g., chlorine, oil, heavy metals). The net effect on the receiving environment is an altered benthic and planktonic community structure, increased chemical and biological contamination of animals such as shellfish, and altered ecological processes because of organic enrichment of sediments. Where these effects are manifested close to shore, especially in situations where the discharge is on or near the beach, the nearshore community may be altered in a way that negatively affects juvenile salmon prey availability. Whether discharges form temporary or permanent barriers to migration is unknown.

The development of the hard bottom community on subtidal and intertidal outfall structures is common and is generally predictable. Fish are often attracted to these structures because of the enhanced production and the fact that they are attracted to a topographic feature in an otherwise homogeneous smooth bottom. Although not known from studies, some species concentrated by the structures may be predators on juvenile salmon (Simenstad et al. 1999).

Intertidal outfalls may act as groins interrupting drift cells, scouring sediments, and converting native beach habitat to cobble or bedrock. These changes may predictably impact the benthic invertebrate and shellfish community, as well as marine vegetation such as eelgrass. Excavation of sediments throughout the intertidal zone will similarly result in damage to a variety of biological resources and ecological processes. In particular, disturbances such as excavation may have at least a short-term impact on areas where surf smelt and sand lance are known to spawn. The rate of recovery from these disturbances is undocumented. Whether these forage fish species will resume egg deposition activities following recovery of the beach substrata is uncertain. It is known from studies at Lincoln Park (Thom and Hamilton 1990) and from areas where clam harvesting is heavy that the natural recovery of the beach bivalve population does occur over a several year period.

Outfalls may affect the six functions of estuaries and nearshore marine habitats for juvenile salmon as follows:

- Migration—disruption of natural corridors and habitats normally used by juvenile fish during construction of outfalls or by their presence, could potentially alter migratory pathways and rates.

- Nursery—similarly, outfall structures as well as discharges alter the structure of the habitats, which may result in loss of vegetation cover normally used by juvenile salmon.

- Juvenile food production and feeding—outfall construction activities and the structure itself can alter habitats where salmon prey is produced. Intertidal outfalls may act as groins, interrupting drift cells, scouring sediments, and converting habitat to cobble or bedrock, thereby modifying the assemblage of preferred salmon epibenthic prey.

- Adult food production—outfall construction activities and intertidal structures can alter nearshore processes and eelgrass/beach habitats where forage fish spawn.

- Residence—outfall structures could modify eelgrass beds and fragment the natural corridor of habitation, reducing protective cover and thus causing the fish to move more quickly through the system.

- Physiological transition—besides the effects of discharge materials (e.g., altered salinity, toxic chemicals; not discussed in this paper) there would be no expected impact of outfall structures on this aspect of the salmon life history.

Artificial Reefs

As detailed above, artificial reefs are well known to be areas of concentration of a variety of fish species. However, it is not known whether fish production is actually increased by reefs. Because of they substantially disrupt habitat structure, change local community structure, and alter predator/prey relationships in an area, artificial reefs may pose a potential impact on salmon and other migratory fish species. Reefs may affect recognized functions of estuaries and nearshore marine habitats for juvenile salmon as follows:

- Migration—reefs, if large and placed in a corridor of migration, could be a temporary barrier to salmon movement. Although not studied, salmon predators could be concentrated at reefs, which may result in increased salmon predation rates.

- Nursery—vegetative cover developed on reefs might provide some refuge for juvenile salmon.

- Juvenile food production and feeding—reefs may cover salmon prey production areas and may modify zones of detritus accumulation used by salmon prey resources (e.g., epibenthic organisms). Adult food production – it is uncertain whether salmon prey would be increased or decreased by reefs. If the reefs are placed on habitats where forage fish are known to spawn, such as eelgrass or high intertidal gravel beaches, adult prey production may be negatively impacted. Residence – reefs could fragment the natural corridor of habitation, thus causing the fish to move more quickly through the system.

- Physiological transition—there would be no expected impact of reefs on this aspect of the salmon life history.

Direct Studies of Biological Impacts

Tide Gates

Tide gates themselves are not particularly large shoreline structures, but they are a critical component of the highly modified dike or levee systems within which they are placed. Dike systems around former tidal marshes are very common in Washington State. These dikes effectively remove large areas to fish passage and rearing**.** The function of the tide gate is flood control. The gate allows the diked land to drain during low tides, while preventing water to enter the system as the tide rises.

Tide gates represent chronic impacts in that they are an obvious barrier to all fish migration when closed; many remain a migration barrier even when open unless specifically designed for fish passage (Bates 1997). Open tides gates may function as fish barriers because of the flow differential across the gate, small opening size, or being perched above the downstream channel. Besides creating significant physical migration barriers, tide gates also impact habitat conditions by blocking salinity and temperature mixing, controlling water level, and causing upstream channel filling (Bates 1997). These physicochemical concentration barriers, habitat modifications, and hydraulic changes likely work together to further impact fish movement upstream.

A recent study in the Skagit River system (WA) examined the effects of a manually gated four-foot diameter culvert installed through a cross levee in 1994 to restore fish access and tidal inundation (Beamer and LaRock 1998) (Table 8). The authors found that the cross levee and manually gated culvert (operated in the full open position) were properly designed and installed, allowing for both upstream and downstream fish passage during April and May 1995. All 11 fish species present downstream of the culvert were also present upstream, and anadromous fish (0+ chum and chinook) were able to successfully navigate through the levee to access foraging habitats. No water quality transition was apparent at the levee after the manually gated culvert was installed, although some estuarine vegetation naturally reestablished on the upstream side.

Tidegates often result in the draining of critically important estuarine wetlands, which leads to the exclusion of juvenile salmon from important rearing, feeding, and refuge areas. Besides altering the vegetation structure and access by fish to the land, the land surface behind the dike often subsides (sinks) significantly in elevation (Thom et al. in prep). Subsidence can often be on the order of a meter or more depending on a variety of conditions. Subsidence is believed to be caused by a combination of factors including elimination of normal sediment accretion processes, decomposition (and loss though gas fluxes to the atmosphere) of organic matter in the peat layer, and dewatering (evaporation) of soils. Restoration of these system through reconnection with tidal hydrology results in recolonization of the sites with native tidal marsh species over a 3-6 year period (Thom 1990, Frenkel and Morlan 1990). However, the vegetation community will not be the same as that found originally on the site, but will resemble a community normally found at the lower elevations. In some cases, subsidence may have been so great that marsh vegetation does not develop, and the land remains unvegetated.

Outfalls

The analysis of impacts from outfall presented here only considers the major physical effects and does not include ecosystem impact associated with the chemicals in the discharge. Most outfall lines that discharge treated waste from municipalities into the subtidal zone are buried through most of their length, and therefore alter the bottom conditions well below the nearshore euphotic zone. Where exposed to water, outfall structures become colonized with encrusting biota. A community typical of very deep subtidal outfalls is dominated by sea anemones (*Metridium* spp.), that may feed on organic particulates emanating from the discharge. Shallower lines are common, and these may be covered by vegetation such as kelp, other seaweeds, and an encrusting animal community.

There are several observations indicating that fish (especially rockfish – *Sebastes* spp.) congregate around these structures (see Artificial Reefs). Higher abundances of fish are often observed relative to areas of barren sand adjacent to the outfall pipe . Although the organic matter emanating from the outfall may enhance food resources for the fish, simply having the structure in place attracts fish (see Artificial reefs). Maps of bottom habitats and fish along the shoreline of King County showed enhanced abundances of fish near outfalls (Woodruff et al. 2000) (Table 8). The outfall structures affect sediment hydrology and sediment dynamics in a manner similar to any other large hard structure, although data on this alteration is not available. Outfall lines, usually located at high current areas, alter sediment distribution by obstructing sediment movement and composition both locally and in surrounding areas.

Perhaps the best studied stormwater outfall in the region is the combined sewer overflow (CSO) at Denny Way in downtown Seattle (Tomlinson et al. 1980, Armstrong et al. 1981). This outfall once discharged untreated wastewater-stormwater directly onto a small beach in Elliott Bay.

Discharges were on the order of once every 3-5 days in winter-spring, and very infrequent during other seasons. The physical effects of the flows was to erode sediments in a swath several meters in width, extending seaward approximately 100m, from the mouth of the outfall. Organic matter enrichment generally increased with proximity to the CSO in areas outside of this scour zone, with highly localized communities of burrowing deposit feeders (e.g., *Capitella capitata*) that are typically associated with organically enriched sediments. These biological trends were evident in the shallow subtidal zone for several hundred meters away from the discharge (Armstrong et al. 1981).

The physical effects of stormwater discharges of much smaller volumes are not documented in the literature. However, erosion of soils and sediments associated with runoff can be expected. This erosion, if severe enough, could result in land loss though landslides.

Artificial Reefs

The long-term impact, and goal, of artificial reef placement is to create a distinctive change in the local biota. Artificial reefs, such as rubble mound structures, may replace or impact one habitat for the sake of another (U.S. Army Corps of Engineers 1980) (Table 8). This means that there is a direct loss of the former habitat. Reefs generally create a greater relief on the bottom, which can alter current flows and deposition-erosion dynamics in the vicinity of the reef. We did not encounter any studies that attempted to quantify this effect. West et al. (1994) found that juvenile and adult rockfish (*Sebastes* spp.) distributions on artificial reefs in Puget Sound were affected by reef depth, vertical relief, and cobble size. In Grays Harbor estuary, addition of oyster shell material over intertidal mudflats resulted in increased habitat complexity, altered prey communities, and a shift in transitory fish species use and feeding (Williams 1994).

In general, location appears to be more important at influencing local assemblage structure than reef structure (Bohnsack et al. 1991). However, many of the most important problems remaining to be addressed deal with the ecological implications of the best use of artificial habitat and their proper role in fisheries management, habitat mitigation, and resource conservation (Bohnsack et al. 1991). Concerns remain in the region as to whether reefs act as “sinks” of fish rather than “sources” of increased fish production (Matthews 1989, Buckley 1997) (Table 8).

Cumulative Effects of Shoreline Modification

Definition

According to Shipman and Canning (1993), the adverse environmental impacts associated with a single shoreline stabilization structure may not always be great. However, there is a growing concern regarding the cumulative ecological effects of shoreline armoring.

A cumulative effect is defined in the National Environmental Policy Act (NEPA, 42 U.S.C. §§ 4321 et seq.) as “the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonable foreseeable future actions regardless of what agency or person undertakes such other actions". Cumulative effects differ from direct and indirect effects (Canning and Shipman 1995b). Direct effects would be those derived directly while an action is taking place. For example, the effects of heavy equipment on beach habitats during construction of the seawall (a short-term effect), as well as direct alteration of habitat at the location where the seawall is placed (a long-term effect) are direct impacts. Indirect impacts might be the erosion of the beach seaward of the seawall that results from a cutoff of sediment supply from the adjacent upland. Cumulative effects would be the incremental loss of beach substrata within a bay that result from incremental additions of shoreline hardening structures in the bay. The overall net effect might eventually be the loss of all potential forage fish spawning habitat in the bay because the soft substrata on the upper shore has been converted to hard pan.

The types of cumulative effects can be grouped into four categories as shown in Table 12. Cumulative effects can result from a single action or multiple actions, and they can produce additive or non-linear results.

Table 12. Types of cumulative impacts (from Council on Environmental Quality 1997).

	Additive Process	Interactive Process
Single Action	Type 1 - Repeated "additive" effects from a single proposed project.	Type 2 - Stressors from a single source that interact with receiving biota to have an "interactive" (nonlinear) net effect.
Multiple Actions	Type 3 – Effects arising from multiple sources that affect environmental resources additively.	Type 4 – Effects arising from multiple sources that affect environmental resources in an interactive (i.e., countervailing or synergistic) fashion

Examples

Because of the complexity and lack of specific data, cumulative impacts are often assessed descriptively. The decline of salmon in the Pacific Northwest may be one of the best examples of a descriptive cumulative impact assessment. Impacts from overharvesting, destruction of habitat, obstruction of migration routes, genetic manipulation, chemical contaminants and climate variability have accumulated to produce a net reduction in salmon populations. Burns (1991), in a review of cumulative impacts on fish, noted that the decline of steelhead and salmon in the Columbia river resulted from cumulative effects which include construction of hydropower facilities. The cumulative loss of about 90% of downstream migrating salmon results from the nine dams in the system even though each dam contributed 4-20% of the loss. It is almost impossible to accurately assess the contribution of all impacts on the salmon populations, or if they are additive or non-linear. However, a relative contribution may be possible to describe based on information from field and laboratory studies, and monitoring.

Fish assemblages within a confined portion of shoreline, such as a semi-enclosed bay, may respond in a similar manner to those in a lake. In a study of fish caught near shorelines in 17 Wisconsin lakes, Jennings et al. (1999) found that sites with rip rapped shores contained greater numbers of fish species. They attributed this result to the fact that riprap provides complex habitat with interstitial spaces for cover and food production. This has often been observed at artificial reefs in marine systems. They found that fish did not respond to shoreline structure, but rather to a suite of habitat characteristics that are the result of the structure, changes to the riparian zone associated with the placement, and intensive riparian zone management on developed properties. Jennings et al. (1999) concluded that although riprap may increase structural complexity at the scale of the individual site, when viewed at the scale of the whole lake conversion of the entire shoreline to one habitat type decreases overall habitat diversity. The effects on marine and estuarine fish may be most pronounced where armoring extends down to subtidal depths, but even placement high in the intertidal zone can remove habitat critical for transient predators (e.g., chinook salmon, staghorn sculpin (*Leptocottus armatus*)) that opportunistically feed in these areas at high tide (Williams 1994).

Armoring can lead to beach loss. In Mobile Bay, Alabama, shoreline armoring has increased steadily since at least the mid 1950's as population has grown in the region (Douglass and Pickel 1999). Here, bulkheading of about 30% of the 100 miles of shoreline had resulted in a loss of 4-8 miles of beach through erosion. The beaches have eroded to such an extent that there is no intertidal zone remaining. The water level never drops below the bottom extent of the bulkhead, creating a condition they refer to as a "bathtub". Douglass and Pickel (1999) conclude that the net cumulative effect of bulkheading would be loss of intertidal estuarine habitats and the conversion of estuarine areas to low diversity "bathtubs".

Scenario for Puget Sound

There are no specific examples of cumulative impact analysis related to shoreline modifications for marine systems in Washington State. Canning and Shipman (1995b), however, highlight the potential for incremental increases in affects and threshold effects on biological processes from shoreline armoring throughout Puget Sound. In Puget Sound, where the tidal amplitude is large, a bathtub scenario would be an extreme result. More often, armored shorelines show lowering and narrowing of beaches, and hardening of the substrata. At Lincoln Park, the beach lowered, narrowed, and hardened dramatically in the 10-20 years following construction of the bulkhead; these effects were noticeable over at least 80% of the length of the bulkhead (Thom, personal observation). The evolution of shoreline erosion on Samish Island also exemplifies the cumulative effects of shoreline armoring at a local scale (Canning and Shipman 1995b, Shipman 1998) (Figure 8). Shoreline armoring structures, some built as early as the 1930's, may have precipitated major changes in shoreline conditions and sediment dynamics on North Samish Island. In response, individual property owners, dealing with the erosion at different times and in different ways, constructed bulkheads to address their erosion and flooding problems. As more bulkheads have been built, beach source sediments derived from natural bluffs have become impounded, further exacerbating erosion conditions on the remaining, unmodified shorelines (Shipman 1998).

For Puget Sound, more information on the length of effect associated with length of armored shoreline is needed to develop a meaningful ratio for cumulative impact assessment. However, it is informative to use a median ratio between the one for Lincoln Park (0.8 beach loss:1.0

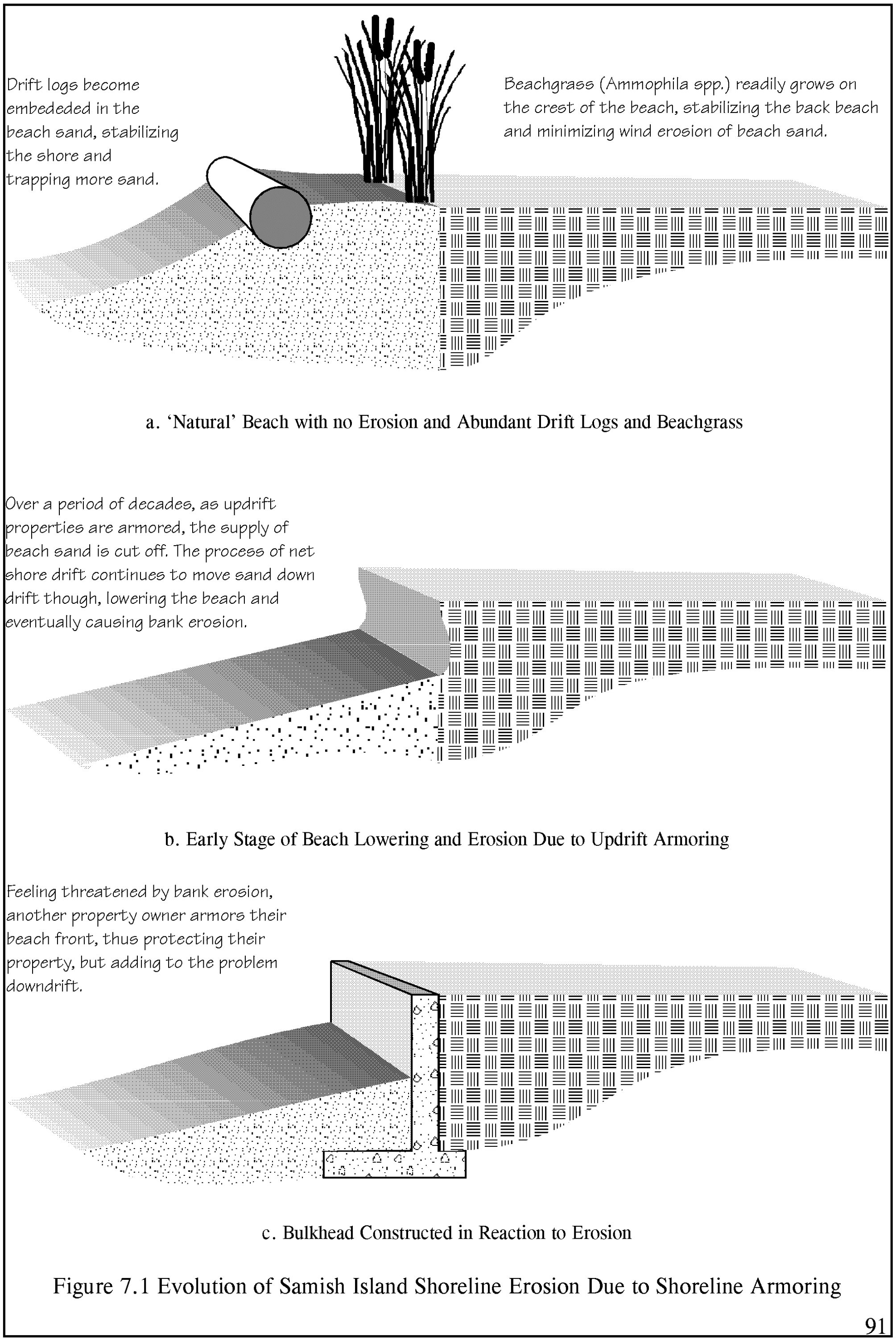

Figure 8. Evolution of Samish Island shoreline erosion due to shoreline armoring (Figure 7.1 from Canning and Shipman 1995a).

armored shoreline length) and the one developed for developed in Mobile Bay (8 miles of maximum beach loss for each 30 miles of bulkheading = 0.27:1) to predict the cumulative effect of bulkheading on beach loss. Applying this median ratio of about 0.5:1 to Thurston County, where 30.2 miles of shoreline has been armored (Canning and Shipman 1995b), results in a predicted cumulative loss of 15 miles of beach. This would mean that many functions, such as forage fish spawning habitat, juvenile salmonid prey habitat and prey production, shellfish habitat, and flow of organic matter from the adjacent uplands, would have been altered or lost from the cumulative effects of incremental armoring of 30 miles of shoreline.

Using this linear ratio may lead to predictive errors. According to the ratio, if all of Thurston County shoreline were armored, 50% of the beach would continue to function normally. However, considering that the sources of sediment to the counties' beaches are limited, there would predictably be a point at which the vast majority of sources would be cut off. Hence, even beaches that were not armored would be starved of sediment, and would erode. This latter condition indicates a threshold after which 100% of the beaches in the county would be affected by shoreline armoring which composes less than 100% of the total shoreline length. At this threshold point, the ratio of beach loss to length of shoreline armored would shift from 0.5 to something greater than 1.0.

Habitat Protection and Mitigation Techniques

A broad array of habitat protection and mitigation techniques exist that can minimize or limit the impact of shoreline modifications to estuarine and nearshore marine areas. Actions that can mitigate these impacts include avoidance (i.e., no shoreline modification), minimization of impacts by using alternative structural modification strategies, land use management, and compensation via restoration of other degraded sites. Obviously, the best way to protect sensitive shoreline habitats is to completely avoid construction in and around these areas (Table 9). Some structural methods of shoreline modification are considered less damaging to nearshore processes and the environment, and are generally considered the preferred approach when critical resources must be impacted. Measures for protecting critical habitats must incorporate principles of landscape connectivity and extend to activities outside of their conveniently defined boundaries. For example, activities in adjacent upland habitats can have profound effects on nearshore marine habitats, whereas watershed practices greatly influence estuarine functionality. Properly designed estuarine restoration projects can return a habitat to a close approximation of its condition prior to disturbance, and in some cases may be used to mitigate impacts to habitats elsewhere.

Structural Alternatives

In cases where wave-energy dissipation is required but large rubble-mound breakwaters or jetties cause excessive impacts, floating wave attenuators may be an appropriate alternative (Cox et al. 1994). Floating attenuators may be constructed of buoyant materials and operate on the principle of reflecting, absorbing, or dissipating wave energy. They are advantageous where offshore slopes are too steep for conventional breakwater designs, or where obstructions to circulation patterns, sediment movement, or fish migration routes must be minimized. While appropriate for many applications in Puget Sound, floating attenuators have several significant limitations, including the inability to effectively reduce propagation of long-period waves, requirement for regular maintenance, limited lifespan, and increased possibility of catastrophic shoreline impacts if the structure fails.

Wall-type breakwaters that are open near the bottom may also be used in cases where negative impacts to bottom habitat, circulation patterns, and fish passage need to be minimized, although the hydraulic and wave reflective properties of these designs on local habitats must still be considered (Cox et al. 1994).

Large jetty designs located at tidal inlets to bays and rivers concentrate coastal flows, alter littoral transport, and impede movement of fish and shellfish adults and larvae. While littoral transport and flow alterations can rarely be minimized due to the inherent design functions and placement needs of large jetty structures, weir jetties present less of a barrier to species entering and leaving an inlet because they remain submerged during part of the tidal cycle. One of the few studies to evaluate this design suggested that the weir allowed planktonic organisms to be transported through the jetty, but was still a barrier to swimming organisms (U.S. Army Corps of Engineers 1981h).

Corrections to shoreline structural design and placement can often reduce alteration of physical processes and minimize impacts to fish and shellfish habitat functions. For example, habitat impacts often occur simply based upon the waterward placement (i.e., tidal elevation) of a hard structure along the shoreline (Engineering Science 1981, Zelo and Shipman 2000). Habitat values can often be protected or restored by designing or relocating the shoreline structure farther landward, where it is exposed to less wave energy. This opportunistic setback approach may also greatly reduce the need to create a highly fortified, and costly structure (Zelo and Shipman 2000).

Vertical or near vertical shoreline stabilization designs (e.g., bulkheads, revetments) that are so prevalent in Puget Sound often displace or alter habitats merely by their shape or slope, resulting in less intertidal habitat. Furthermore, these designs often result in high reflective wave energies that increase erosion rates shoreward and in adjacent areas. Modifying the slopes of these structures by integrating vegetated or riprapped bench areas can enhance tidal ranges and change hydraulic conditions to allow beneficial vegetation and sediment retention (Zelo and Shipman 2000).

Many of these same vertical concrete designs have limited wave dissipation capabilities and exhibit little structural complexity that might enhance use by marine organisms. Integrating more gradually sloping stone matrices in a variety of sizes will increase the wave absorption capabilities of the structure and enhance habitat diversity for a variety of marine resources (Zabawa and Ostrom 1982, Thom et al. 1994a). Examples of alternative designs include berm or buried revetments that use a thick, mobile layer of gravel, cobble, or traditional stone material to dissipate wave energy and conform to the beach in more natural contours (Cox et al. 1994).

Elevated designs for shoreline access, such as marine railways or elevated concrete ramps, are additional approaches to protecting sensitive forage fish spawning areas and minimizing adverse impacts on habitat.

As previously described, innovative soft stabilization approaches involve natural materials that deform and adjust over time to changing shoreline conditions, and often cause minimal impacts to nearshore habitats (Cox et al. 1994, Zelo and Shipman 2000, Macdonald et al. 1994). These methods include beach nourishment with sand and gravel substrates, biotechnical approaches that involve vegetation planting, and anchoring of large woody material to the shoreline.

As previously mentioned, sand and gravel “blankets” have also been used as an mitigation approach to establish productive communities of epibenthic salmonid prey species in Elliott Bay, Commencement Bay, and elsewhere in the Pacific Northwest (Parametrix 1985, Simenstad et al. 1991c). Typically, these mitigation sites are designed to provide productive feeding, rearing, and migratory areas for juvenile salmonids by constructing low gradient, shallow habitat with fine-grained substrates. Often, deep subtidal habitat is converted to intertidal and shallow subtidal habitat by placing select fill or dredged material into subtidal areas to build habitat up to an elevation above –10 ft MLLW.

Non-Structural Management Alternatives

The processes influencing estuarine and nearshore marine habitats operate within a much larger, heterogeneous landscape. The components of this landscape include a variety of other interacting ecosystems, such as adjacent upland habitats and their watersheds (Thom et al. 1994a). The principles of landscape connectivity suggest that human actions outside of conveniently defined habitat boundaries can influence other critical habitats (Shreffler and Thom 1993). In practice, management practices in watersheds and upland habitats can have profound effects on estuarine and nearshore marine habitat structure and function. Typical management activities in adjacent uplands that influence bluff and shoreline stabilization and water quality include building setbacks, storm and groundwater management, and vegetation management (Downing 1983, Cox et al. 1994, Macdonald and Witek 1994, Zelo and Shipman 2000).

Building setbacks describe the process of constructing sensitive shoreline structures (i.e., homes) a safe distance from eroding shorelines or bluffs (Terich 1987). Setbacks are considered the safest and least expensive alternative to avoiding these hazards along Washington’s erosive coastlines (Terich 1987, Downing 1983, Komar 1998). Other advantages of this approach include continued operation of natural shoreline processes, no impacts to neighboring properties, preservation of beach aesthetic and recreational values, preservation of beach flora and fauna, few maintenance costs, and no permit problems (Terich 1987, Downing 1983) (Table 9). Safe setback distances vary with location but can be determined from neighboring structures and regional guidance documents (Macdonald and Witek 1994).

Surface and groundwater management is another nonstructural approach to reducing erosion around sensitive shoreline structures and property (Myers et al. 1995). Water is one of the most common agents of slope instability and erosion, and water supplementation should be kept to a minimum on erosion-prone hillsides and slopes (Myers 1993). Excessive runoff and infiltration produced by irrigation, drainage of impervious surfaces, and sanitary drainfields can place additional demands on the drainage capacity of coastal bluffs (Terich 1987, Downing 1983). Seeps in slopes often indicate groundwater drainage patterns and areas of potential instability. When groundwater drainage is blocked or infiltration rates increase rapidly, hydrostatic pressures rise and enhance the threat of landslides (Downing 1983). Surface water runoff should be monitored during periods of heavy rainfall; runoff that concentrates in rills and channels will eventually downcut through the slope, creating more severe slope stabilization problems as erosive forces increase. Concentrated surfacewater discharges may also have catastrophic erosive effects to beaches, potentially leading to dune overwash, wave-induced flooding, downdrift erosion, and rip currents. These problems may be countered by providing ponding basins for groundwater recharge, discharging water at hardened shoreline features (i.e., rocky headlands), diverting runoff to inland waterways, or pumping the drainage offshore (Smith 1997). Few studies have documented the benefits of ground and surface water management, although several have shown the deleterious effects of poor practices, which can lead to eutrophication and harmful algal blooms in receiving water bodies (Smith 1997, Myers et al. 1995, Short and Burdick 1996).

Upland and riparian vegetation management encompasses vegetation removal and trimming activities, as well as planting deep-rooted upland vegetation to increase soil stability and reduce erosive hydrologic forces on shorelines (Manashe 1993). Live plant foliage and forest litter break the force of falling rain, reduce surface water runoff velocity, and increase the absorptive capacity of soil, whereas plant roots provide a fibrous web that stabilizes and anchors soil. Therefore, maintenance of existing vegetation and revegetation of bare ground on bluffs with native trees, shrubs, and herbs can improve slope stability by trapping sediment and controlling surface runoff (Cox et al. 1994, Manashe 1993) (Table 9). Besides reducing erosive forces, riparian vegetation is a key element of shoreline ecological function and has a significant influence on habitat value, both in the riparian zone itself, and in adjacent aquatic and terrestrial areas (Zelo and Shipman 2000, Brennan and Culverwell in prep). Riparian vegetation contributes to maintenance of fisheries habitat and water quality, functioning as shade, cover for fish and wildlife, organic matter input, and source of insect prey (Levings et al. 1991, Thom et al. 1994a). It may have particularly high value in Puget Sound because of its contributions to marine forage fish that utilize the upper intertidal for spawning (Pentilla 2000) and to juvenile salmonids for cover and foraging (Thom et al. 1994a).

Estuary Restoration

Background

Estuarine restoration projects are designed to result in a net positive benefit to ecological habitat, processes and functions, and ultimately, resource species. There are numerous definitions of restoration. Perhaps the most relevant to the shoreline ecosystems of Washington state are those put forth by the National Research Council (NRC) and the Society of Wetland Scientists (SWS). The NRC (National Research Council 1992) defines restoration as “the return of an ecosystem to a close approximation of its condition prior to disturbance”. With restoration, ecological damage to the resource is repaired, and both the structure and function of the ecosystem are recreated. Wetland Restoration is defined by Society of Wetland Scientists (2000) as: “actions taken in a converted or degraded natural wetland that result in the reestablishment of ecological processes, functions, and biotic/abiotic linkages and lead to a persistent, resilient system integrated within its landscape. Within this statement by the SWS, is embodied the following principals:

- Restoration is the reinstatement of driving ecological processes, which include the fundamental forces that maintain wetland ecosystems such as hydrology, geomorphic setting, physical processes (e.g., fire, sediment movement), biological processes (e.g., competition, decomposition, predation), and biogeochemical processes (e.g., nutrient cycling). Together, these fundamental forces interact to drive the ecological functions and produce wetland structure. By successfully restoring the structure, the functions associated with that structure will manifest themselves. It is important to investigate the root cause for the loss of function, and link restoration to actions dealing with the root cause (Mitsch et al. 1998, Zedler 1996, Malakoff 1998).

- Because the landscape health and processes are critical to the recovery of a site that is to be restored, restoration projects must be integrated with the surrounding landscape. Integration into the landscape is essential to the formation and long-term maintenance of ecosystems (Brinson 1993, Bedford 1996).
- The goal of wetland restoration is a persistent, resilient system that is not static but rather has enough of the physical and biological processes intact that it can respond to disturbances without human intervention (Mitsch 1998).
- Wetland restoration should target as a goal the historic state of the wetland. However, a variety of factors (e.g., successional stage, seed bank conditions, disturbance history, etc.) may prevent establishment of the communities and biological structure present prior to human disturbance even when the driving processes have been restored.
- Restoration planning should specify structural and functional objectives and performance standards for measuring achievement of these objectives. It is critical that we learn from our successes and failures, particularly in the relatively new field of wetland restoration.

Restoration in Washington State

A number of restoration projects in Washington State have focused on nearshore marine and estuarine systems. Estuary restoration has focused on removal of dikes, which cut off huge areas to salmon production, and revegetation of degraded marsh or flat areas. In the marine nearshore, restoration of eelgrass habitat is probably the most commonly practiced form of habitat restoration (Thom 1990, Martz et al. *eds*1994, Shreffler and Thom 1995, Thom et al. 1997, Yozzo and Titre 1997). Few studies have examined the direct benefits of shoreline structure removal. However, this type of restoration is receiving some attention (Commencement Bay Natural Resource Trustees 1997).

In Washington State, restoration projects are often carried out as compensatory mitigation for impacts caused by a coastal development project. Examples of habitat restoration projects in estuarine and nearshore areas in Washington include the following:

- Dike breaching to restore tidal marshes
- Removal of bulkheads and overwater structures to restore upper intertidal and riparian habitat
- Renourishment of beaches with fine sediment to restore forage fish spawning habitat
- Excavation of fill to restore tidal marshes and tideflats

- Establishment of eelgrass (*Zostera marina*) in formerly degraded areas
- Remediation of contaminated sediments or removal and replacement with clean material

In addition, restoration actions can include construction of a structure in water (e.g., jetty) or placement of fill, which are required to create conditions conducive to full development of the restoration potential for the site. Restoration of fish habitats, using sedge marshes and eelgrass beds, has been explored as a technique for achieving sustainable development in coastal areas (Levings 1991). Examples exist where structures are utilized to achieve restoration of selected ecosystem functions. For example, shoreline development such as a floating fishing pier might reduce wave action to the same degree that mud and sand flats did in the area prior to shoreline development. This action may result in restoration of a salt marsh/eelgrass complex. However, most times structures are used, the result is considered habitat enhancement and not restoration.

In most cases of estuarine restoration, it is intended that short-term negative impacts be offset substantially by the positive ecological benefits derived from the restored system. However, most restoration actions will incur impacts during implementation (i.e., construction), and potentially for some time after implementation. The initial and long-term impacts are very poorly documented.

Restoration actions that meet the NRC (1992) definition can involve the following approaches (Shreffler and Thom 1993):

- Source control (i.e., reduction or elimination of disturbances or contaminant input, followed by ecosystem recovery)
- Restoration to predisturbance conditions (i.e., before any human impact)
- Restoration to historic conditions (i.e., very minimal human impact)
- Enhancement of selected attributes (e.g., enhance a marsh habitat for a selected species)
- Creation of a new ecosystem (i.e., build a system not previously present at a site)

The latter two approaches may not be true restoration. Enhancement of selected attributes often means that a habitat is made larger. However, enhancement can also refer to remediation of poor habitat functions through improvement of conditions. Although not restoring a previous habitat or system at a site, creation can restore previously existing ecological functions. For example, filling of a dredged area within a bay that has been entirely altered will restore shallow water habitats and *functions*, but not necessarily be exactly the same habitat *structure* that existed at that site historically. In some instances, creation may be the only viable alternative for restoration (NRC 1992).

The potential for success of each of these approaches varies depending on the degree of disturbance that exists at the site and the degree of disturbance of the landscape where the restoration site is located (Figure 9). Where disturbance of the site and the landscape are low, restoration to predisturbance conditions may be possible, and the potential for success may be high. Conversely, a highly disturbed site within a highly disturbed landscape may have a poor probability for success and only enhancement of selected attributes and creation of a new ecosystem may be possible approaches.

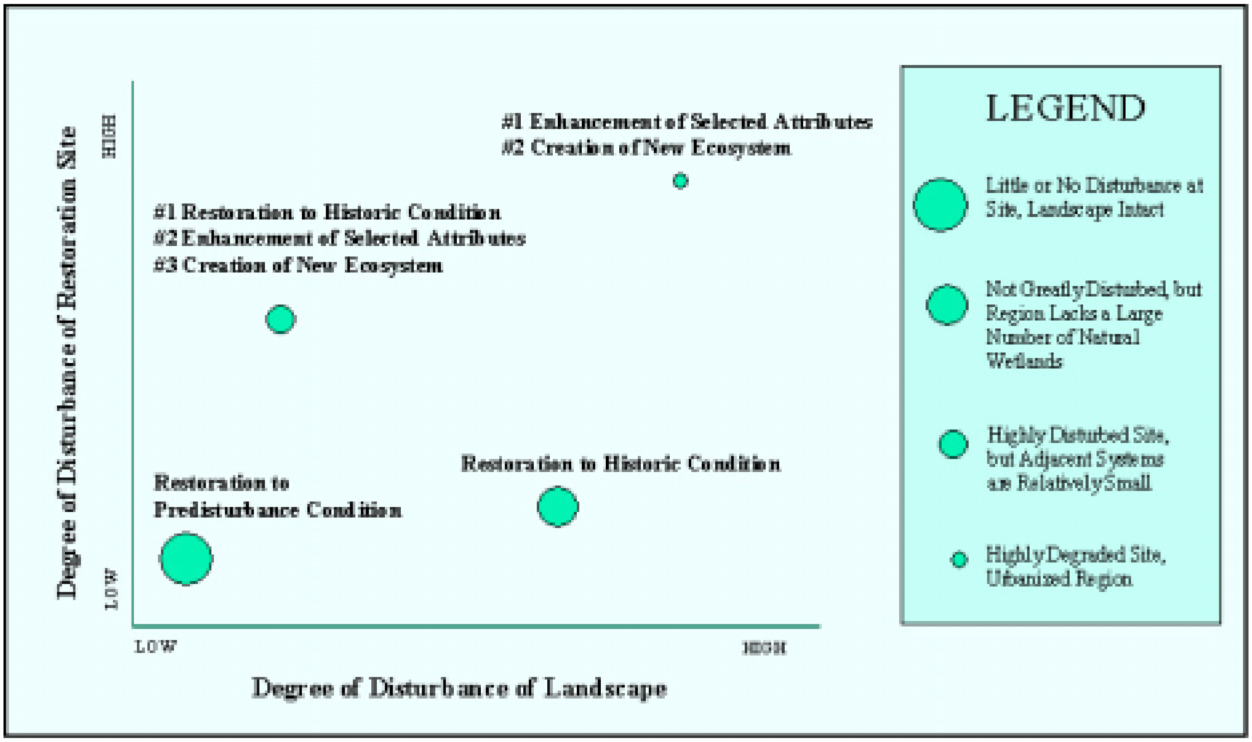

Figure 9. Relative potential for successful restoration. Potential success increases with the size of the circle (from Shreffler and Thom 1993).

Direct Studies

General Restoration Projects Results

Examples of restoration projects from Washington State are shown in Table 13. Most of the impacts are either not documented or reported, but are considered potential. Almost all occur in moderately to highly urbanized areas where benthic habitats have been severely damaged or altered. The primary impacts occur through alteration of existing habitat by placement of fill or loss of existing habitat functions.

Table 13. Examples of estuarine and nearshore remediation, creation, habitat enhancement and restoration projects in Washington and Oregon, along with potential impacts.

Project (references)	Primary Restoration Goal	Initial Impact	Long-Term Impact
Gog-le-hi-te (Simenstad and Thom 1996)	*Restoration*: excavate tidal marsh; juvenile salmon use	Release of sediment to river	Trapping litter and debris
Tacoma Kraft Mill Sediment cap (Parametrix, Inc. 1988)	*Enhancement*: Uncontaminated tidal flat habitat	Fill placed on existing habitat	Potential recontamination of cap
Lincoln Park beach renourishment (Antrim and Thom 1995)	*Restoration*: intertidal soft bottom habitat; juvenile salmon use; protect Park	Release of sediment to river Fill on existing habitat	Loss of kelp Periodic renourishment required
Jetty Island Bay (Houghton et al. 1995)	*Creation*: productive bay for shorebird and fish use	Fill on existing habitat	Gradual erosion of fill Periodic renourishment required
Spencer Island Marsh (Tanner 1993)	*Restoration*: breach dike restore tidal marsh and use by juvenile salmon	Sediment release	None
Clinton Eelgrass (Thom et al. 1999)	*Restore*: eelgrass habitat by planting	Plant donor stock damage	None
Milwaukee Waterway Beach (Commencement Bay Nat. Res. Trust 1997)	*Creation*: intertidal sandy beach for fish and bird use	Underwater dike placement Fill on subtidal habitat	Loss of subtidal soft bottom habitat
Chehalis Slough (Simenstad et al. 1997)	*Creation*: tidal slough and marsh; juvenile salmon use	Sediment release	Loss of swamp habitat
Elk River salt marsh (Thom et al. in review)	*Restoration*: dike breach to restore tidal marsh functions	Sediment release	None
Grays Harbor Shell (Armstrong et al. 1991)	*Enhancement*: shell placement to increase young Dungeness crab survival to adulthood	Shell placed on natural tideflat and eelgrass	Loss of tideflat function Requires renourishment of shell
Schel chelb tidal system (Patmont and Singer 1998)	*Restoration*: excavate to restore tidal marsh/flat system for birds and fish	Some forested and wetland habitat lost	Loss of former habitat functions
South Slough Watershed Restoration (Rumrill and Cornu 1995)	*Restoration*: breach dikes and create "cells" of tide marsh at various elevations	Some freshwater wetlands were filled	None
Salmon River salt marsh (Frenkel and Morlan 1990)	*Restoration*: breach dike to restore tidal marsh	None reported	None
Removal of *Spartina alterniflora* using a herbicide (Kubena et al 1997)	*Restoration*: natural unvegetated tide flats	Suspected toxicity to invertebrates not proven by bioassay	Not investigated
Habitat enhancement in the Duwamish River estuary (Simenstad and Cordell 2000)	*Enhancement*: provide productive feeding areas for juvenile salmon	Unknown	Improvement of existing degraded habitat

In the case of the Grays Harbor shell project, shell has replaced functional tideflat and, to a lesser degree, eelgrass habitat (Armstrong et al. 1991). The ultimate aim of this project was to offset channel dredging related losses of Dungeness crab (*Cancer magister*) to the fishery by increasing availability of intertidal shell habitat. This structurally complex shell hash is preferentially chosen by crab megalopae for settlement, and provides increased refuge, food, and survival over mudflat habitats. Although the project was designed to *restore* a particular resource (i.e., the crab lost because of the dredging project), it does not fit well with the SWS definition of wetland restoration and may not be considered restoration by some. Damage to eelgrass habitat was avoided by both pre-placement survey and delineation and during placement by an observer who directed shell placement around isolated patches of eelgrass. These isolated eelgrass patches prospered and became noticeably more robust (i.e., enhanced productivity) in subsequent years as they were protected from erosion and thrived better in the ponded water conditions caused by surrounding shells. However, as the shell gradually sank and the shell plot reverted to former bare mudflat conditions, the eelgrass eventually declined to former abundance levels.

There may be short-term initial impacts associated with any restoration project. These generally should dissipate with time. Longer-term impacts result when there is a large physical change made to the area. For example, the creation of the back bay at Jetty Island resulted in permanent filling of a portion of the intertidal zone. Renourishment of the fill will be required, which may also result in a short-term release of suspended material (Houghton et al. 1995).

Eelgrass

Eelgrass restoration is commonly proposed for compensatory mitigation in Washington State as well as in California. Seagrass restoration has for the past 30 years or so been a major mitigation option nationally (Fonseca et al. 1998). In a review of eelgrass transplant projects along the U.S. West Coast up until 1989, Thom (1990) found few successful projects. The primary reason for failure of most projects was that controlling factors at the site were not correct for eelgrass growth. Since 1990, more projects in the region have met with better success primarily because site conditions have been considered more carefully.

Robert Hoffman of the National Marine Fisheries Service, Long Beach, California, has maintained a database of eelgrass transplant projects conducted in California since 1976 (Table 14; Hoffman 1999). The database contains now contains a list of 39 projects that had been completed (i.e., constructed) between 1976 and 1998, and two that were scheduled for completion in 1999. The projects range in size from <0.1 ha to 4.8 ha. By comparison, the final target area proposed for restoration of eelgrass at Middle Harbor (San Francisco Bay; Thom et al. 2000) alone is approximately 7 ha. The projects are judged successful if there is a net increase in eelgrass coverage. Based on this criterion, 14 (37%) of the projects were considered successful, 5 (13%) were partially successful, 7 (18%) were not successful, and 13 (37%) were pending the results of monitoring studies. Most projects (61%) are smaller than 0.1ha in size. Average project size has increased through time, as has the percent rated as successful. Of the eight projects larger than 1.0 ha, three have been successful, one was partially successful and four are pending.

Table 14. Summary of eelgrass projects in California from Robert Hoffman (1999). (Projects listed as <0.1ha were included in averaging as 0.05ha).

Year	Number of Projects	Mean Size (ha)	Max. Size (ha)	Success (%)
1976-79	4	0.4	1.6	25
1980-84	3	0.6	1.7	33
1985-89	12	0.6	3.8	58
1990-94	9	0.3	2.0	56
1995-98	11	1.0	4.8	all pending
1999	2	2.0	4.0	planned

Merkel & Associates, Inc. (1998) summarized information from 47 eelgrass and shallow water habitat restoration projects spanning from San Diego to Vancouver, British Columbia. Many of these were also included in the list compiled by Hoffman on California projects (Hoffman 1999). Success of the eelgrass projects ranged from less than 10% to 100% annually, with success improving through time. Focused mitigation and enhancement projects have resulted in a cumulative increase in eelgrass area along the Pacific Coast since 1985. Prior to that, eelgrass was being lost through poor eelgrass transplanting success. The authors found that site manipulations had an effect on eelgrass transplant success rate. Projects involving fill, excavations, or with protection from waves had success rates greater than 90%. In comparison, the success rate on unmanipulated sites was approximately 38%. Based on the data presented, it is not known whether many of the projects involved enhancement or creation rather than restoration.

After reviewing seagrass restoration projects nationally, Fonseca et al. (1998) concluded that seagrass plantings that persist and meet the size criteria provide many of the functional attributes of natural beds. Monitoring of eelgrass restoration projects in Puget Sound have shown that macrofauna such as Dungeness crab and demersal fish occupy the planted areas almost immediately after planting. In addition, transplanted plots over one year old harbor prey of juvenile salmon in densities very near those found in reference meadows. Other functions such as substrata stabilization, nutrient cycling, and enhancement of larval settlement and survival are in need of study to fully understand the development rates and dynamics of these functions.

Fonseca et al. (1998) state that seagrass planting is no longer experimental but:

- Planning, planting, and monitoring requires attention to detail and does not lend itself to oversimplification

- Success rate of permit-linked seagrass mitigation projects remains low, but appears to result from failures in the planning process, as much as any other cause

- Improvements are needed in site selection, care in planting, and incorporation of plant demography

- Seagrass plantings that persist and generate target acreages have been shown to quickly provide many of the functional attributes of natural beds.

There is a growing awareness that eelgrass restoration will require donor plant material. Large projects would require extensive amounts of eelgrass, which is most often gathered from nearby meadows. To date, there have been no quantitative assessments of the impact of eelgrass removal on donor beds. Observations have indicated that if removal is spread over a large area, damage to the meadow is minimal and recovery is rapid (Battelle Marine Sciences Laboratory, unpublished information).

Physical Short and Long-term Effects

The list of projects in Table 13 above provide a sampling of the common types of restoration, creation, and enhancement projects undertaken in the Northwest. There are many more projects, but there is often a lack of systematic reporting of results in a format that is readily available for review. Furthermore, the impacts from restoration projects are often not summarized in the reports that are made available. We can find no specific reasons why the impacts summarized in Table 13 cannot be generalized to other projects of a similar type.

Many restoration projects in estuaries and nearshore systems in the region are specifically designed to benefit salmon. Hence, short and long-term impacts associated with construction and operation of the projects are considered to be small or insignificant relative to the long-term benefit to salmon. In summary, the short term and long term affects of restoration project construction and operation on the six functions of estuaries for juvenile salmon are as follows:

- Migration—restoration projects may temporarily obstruct the migration corridors during construction. For example, projects involving placement of fill, dike removal, and excavation often require operations in water with heavy equipment. These operations would be disruptive to the migration of young salmon along that part of the shoreline. The increased turbidity, noise, presence of equipment, general boat activity would be sources of disruption. Present regulations do not allow projects where there is any potential for affecting juvenile salmonid migration, to occur during the primary outmigration period in late winter though early summer. Fill placed on flats to create an embayment, such as was done on Jetty Island, may affect migration patterns over those flats. However, these and other projects where habitats are restored, opened, or created, are specifically designed to *attract* salmon into them, thus altering their migration patterns for beneficial reasons.

- Nursery—restoration projects that place fill or reduce the area or quality of natural nursery areas in any way would affect the nursery function.
- Juvenile food production and feeding—salmonid food production is a function of habitat type and season. Projects that alter both the main habitat types, such as eelgrass, tidal flats and marsh edges, and are proven to produce prey resources for juvenile salmon, will affect this function.
- Adult food production—similarly, projects where fill or excavation occurs on beaches where forage fish are known to spawn, will have a negative impact on forage fish production and availability.
- Residence—Most restoration projects are done with the knowledge that the integrity of the ecosystem needs to be restored in order to provide the most benefit for salmon. Restoring integrity means that the fish will receive the maximum benefit from their residence and use of the system. However, fill placement or other shoreline modifications could fragment the natural corridor of habitation, thus causing the fish to move more quickly through the system.
- Physiological transition—restoration should benefit this function by increasing residence time toward more natural levels.

There are also a number of situations encountered in estuarine restoration that are related to site conditons and biological considerations. Systems may recover without any intervention, but this can take decades to millennia depending on the degree of disturbance to the system. The goal in restoration is to *move as quickly as possible* from a disturbed or altered condition to one that provides historical ecological conditions. Hence, the factors that interfere with the rate and dynamics of restoration must be considered. Commonly encountered problems in restoration projects in Washington State include *site subsidence* (i.e., the elevation of a marsh will decline once it is behind a dike), *erosion*/*sedimentation*, *predation*, and *invasion of undesirable species*. All of these factors can interfere with the rate and dynamics of restoration at a site. This is important where restoration is used as compensatory mitigation, and where restoration of a site is critical to such functions such as public safety (e.g., flood control) or endangered species recovery (e.g., nesting habitat for bird species).

Site Subsidence

The recovery of diked tidal marshes has been fairly well studied in the Pacific Northwest. These studies have shown that a system will show rapid and dramatic shifts in vegetation communities over the first 4-6 years following dike breaching (Frenkel and Morlan 1990, Thom et al. in revision). However, because the elevation of the marsh surface normally subsides up to a meter or more, the vegetation community that develops differs from the community that originally occupied the site prior to diking. The difference will persist for at least 20 years and perhaps up to a century or more while the marsh builds elevation through trapping of sediment and organic matter (Thom 1992).

Erosion/Deposition

Vegetated tidal habitats buffer waves and, thereby, can stabilize shallow water habitats. Often, however, the depositional and erosional processes are not well understood at a restoration site. Extensive erosion can take place before vegetation communities are dense enough to slow this process. Concordantly, sediment can accumulate within a system in catastrophic amounts so as to alter the morhpology of the system before it matures. Erosion and deposition have been documented in the restoration of a variety of systems, including several dike breach, excavation, and eelgrass restoration projects listed in Table 13. Gog-Li-Hi-Te wetland was devastated in the second year of its existence by a major flood-driven deposition event that covered much of the area with sediment (Simenstad and Thom 1996). During its first spring, a flood deposited large amounts of woody debris over most of the site, resulting in loss of some of the transplanted sedge plants. The system appears to have stabilized after almost 15 years, but the actual vegetation community structure differs dramatically from that predicted for the site.

Predation and Herbivory

Predation and herbivory present significant problems at times to restoration projects. For example, establishing tidal flow and shallow protected habitat for salmon can result in enhanced feeding opportunities by predatory waterfowl, such as great blue herons, that capture juvenile salmon in shallow channels in these systems. For a restoration project designed to enhance juvenile salmon habitat, this may represent a negative function of the restoration site; however, it represents a positive habitat functional attribute for birds. There are numerous reports of Canada Geese grazing and removing vast numbers marsh plants during the early phase of restoration projects. A number of strategies have been applied to try to reduce herbivory on the newly planted material including fences, reflective tape, dogs, and cages. It appears that cages that fully surround the planted area are most effective (Charles Simenstad, personal communication).

Undesirable Species

Invasion of undesirable species such as purple loosestrife (*Lythrum salicaria*), smooth cordgrass (*Spartina alterniflora*), reed canarygrass (*Phalaris arundinacea*), and even cattails (*Typha latifolia*) can be very problematic (Frenkel and Morlan 1990, Simenstad and Thom 1996). Often these undesirable species are highy invasive and can dominate new and developing habitats. Measures can be taken to try to exclude, or at least reduce the causes for, undesirable species invasions of restored systems. These include removal of seed sources near the site, eradication of the invading species before they become abundant, dense plantings of desirable species, and designing restoration site conditions to be unfavorable to these species.

Other Lessons

It is clear that before restoration is attempted at a site, there must be a careful site assessment. The site assessment provides evidence about the suitability of the site for restoration and about what type of restorative actions must be taken (Zedler 1996, Callaway et al. 1997, Thom 2000). The assessment can employ experimental studies that indicate whether a certain plant species can survive and flourish at the site. Because restoration is essentially an experiment and results are uncertain, it is appropriate to incorporate experiments into the restoration program. For example, the restoration projects on the South Slough in Coos Bay, region, have manipulated elevation to evaluate the effect of this factor on salt marsh development (Craig Cornu, personal communication). Experimental plantings of eelgrass at a site prior to large scale planting can provide critical data regarding whether a site is suitable for eelgrass restoration (Fonseca et al. 1998). Since tidal channel morphology and location are difficult to predict, many times it is appropriate to let the hydrology of the site naturally grade the channels rather than excavating channels prior to returning hydrology to a site (Simenstad and Thom 1996).

Adaptive Management

Because of the uncertainty in precisely predicting the outcome of restoration projects and the natural variability in the environment, there is uncertainty with any restoration project (Thom 2000). The best way to deal with uncertainty is thorough planning and site assessments, and incorporation of a strong and well-planned adaptive management program. This program should include a clear goal for the project, monitoring to assess the progress toward the goal and a framework for making decisions about mid-course corrections. Funding, so often lacking, must be made available to implement the adaptive management program. This approach will enhance the probability for net benefit to the environment. Thereby, the risk of potential damage to the environment from failed projects can be minimized.

Summary of Existing Guidance

Available Guidance Materials for Activities/Features Impacting Marine and Estuarine Shorelines

- Index of Washington State laws (Revised Code of Washington (RCW)) administered by the Department of Ecology - http://www.ecy.wa.gov/laws-rules/ecyrcw.html

- Index of Washington State rules (Washington Administrative Code (WAC)) administered by the Department of Ecology - http://www.ecy.wa.gov/laws-rules/ecywac.html

- Shorelands and Environmental Assistance Program. 2000. Proposed Shoreline Master program Guidelines Rule Amendment (WAC 173-26, Part III and Part IV): Final Environmental Impact Statement, (Publication 00-06-020), Washington Department of Ecology, Olympia, Washington. - http://www.ecy.wa.gov/biblio/0006020.html

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

- Hood Canal Advisory Commission. 1977. Hood Canal Handbook. 184 pp.

- Washington State Department of Fish and Wildlife. 1998. Policy of the Washington Department of Fish and Wildlife Concerning Marine and Estuarine Habitats. Washington State Department of Fish and Wildlife. (Draft) 19 pp. Olympia, Washington.

- Washington State Department of Fish and Wildlife. 1997. Policy of the Washington Department of Fish and Wildlife and Western Washington Treaty Tribes Concerning Wild Salmonids. Washington State Department of Fish and Wildlife. 46 pp. Olympia, Washington.

Summary and Recommendations for Guidance Document

Summary of Other Literature Reviews

The biological impact of structural shoreline stabilization methods has been the subject of several thorough literature surveys (Mulvihill et al. 1980, Simenstad et al. 1991b, Macdonald et al. 1994, Thom et al. 1994a, Kahler et al. 2000). In each of these reviews, the authors concluded that a preponderance of circumstantial evidence exists to link observed changes in shoreline physical processes to biological impacts. However, each report highlighted the pervasive lack of controlled studies directed at documenting and understanding the biological impacts of shoreline modifications.

Simenstad et al. (1991b) conducted a thorough literature survey of the effects of estuarine habitat modification on anadromous salmonids in the Pacific Northwest. References on the subject were categorized by the following criteria: *direct* references detailed impacts of a particular structure to salmonids, *indirect* discussed general impacts of habitat manipulation to salmon prey species or their environment, but not salmon specifically (see Conceptual Model section, above), *background* described environmental requirements and behavioral characteristics of salmonids, but did not deal with shoreline modifications, and *outside* discussed impacts of shoreline modifications on salmonids in other systems (e.g., freshwater). They found only 24 studies that directly assessed the impact of shoreline modifications to salmonids, and of these, few applied rigorous, hypothesis-based testing that confirmed these impacts. Rather, the majority of studies relied upon indirect or background evidence to assess impacts, with a number of comparable outside studies that provided adequate inference to suggest that impacts would occur. They concluded that the literature base and existing state of knowledge was currently inadequate to provide information needed to develop an impact assessment protocol (Simenstad et al. 1991b).

Macdonald et al. (1994) and Thom et al. (1994a) provided comprehensive reviews of the effects of shoreline armoring on Puget Sound coastal physical processes and biological resources, respectively, as part of a coastal shoreline erosion management strategy. Macdonald et al. (1994) found that although extensive studies on shore protection impacts to physical processes were conducted in other parts of the country, very few were available or applicable for Puget Sound. They found that the most significant impacts to physical shoreline processes were impoundment of potential natural sediment sources behind shoreline structures, which resulted in a cascade of indirect impacts, including altered sediment downdrift and grain-size, wave hydraulics, and drainage regimes. Thom et al. (1994a) noted that whereas there was ample evidence illustrating the various effects of shoreline armoring on habitat structure in Puget Sound, the biological effects (e.g., loss of spawning habitat, shoreline cover, food resources, and migratory corridors) were poorly understood and not well documented. Consequently, they found that most conclusions were based on anecdotal information and inferences about known ecological processes (i.e. established links between physical conditions, habitats, and biological resources).

Similar reviews have been conducted for freshwater systems in the region. Kahler et al. (2000) summarized the impact of artificial structures and shore zone development on salmonids listed under the Endangered Species Act to determine the current state of knowledge for the City of Bellevue, Washington. Although primarily focused on lakes within King, Pierce, and Snohomish counties, the review also included recent pertinent literature on marine and estuarine habitats. As with the previous reviews, the authors' found that the amount of basic research providing information on responses of fish to shoreline structures was very limited (Kahler et al. 2000). Their primary recommendation, to prevent structural simplification of shore zone habitat (e.g., riparian cover, LWD), was based primarily on intuitive relationships between shorezone development and loss of properly functioning shore zone habitat.

An extensive, nationwide review of the biological impacts of minor shoreline structures was conducted by Mulvihill et al. (1980) as a guidance document for the U.S. Fish and Wildlife Service. Over 550 references were reviewed and categorized by region, structure type, and relevance. Mulvihill et al. (1980) found that the bulk of the information on effects of shoreline structures was engineering-oriented, while an equally large body of literature documented the distribution and tolerance limits of nearshore biota. Again, these authors concluded that very little information existed on the impact of structures to the biota, and a majority of studies were nonexperimental. This generally resulted in "watered-down" impact assessments that relied upon the "ability of individuals to extrapolate from what they know of the construction procedures, coastal physical processes, and nonstructure related biological data" (Mulvihill et al. 1980).

Conclusions

This report attempts to outline the interactive factors linking shoreline modifications to impacts on nearshore biological resources of Washington State, while emphasizing fundamental research needs critical to better evaluating these links. Throughout the document, we attempt to point out where the research supports assumptions and hypotheses, while also indicating where the data is notably absent. In the following text, we provide a summary of our major findings, followed by recommendations for guiding management of these actions.

Washington State's nearshore ecosystem plays a critical role in support of a wide variety of biological resources, many of which are commercially, culturally, aesthetically, and recreationally important to the people of the region. These resources include numerous species of invertebrates (e.g., shellfish), finfish (e.g., salmonids, groundfish), and birds, as well as the living resources that provide feeding and refuge functions.

Nearshore and estuarine resources of Washington State have been severely impacted by shoreline modifications. Over 29% of Puget Sound's shoreline is stabilized by structures, with

1.7 miles of Puget Sound shoreline being newly armored each year (Canning and Shipman 1995b). In King County watershed resource inventory areas (WRIAs) 8 and 9 alone, recent surveys have shown that armoring comprises 75-87% of the coastline (Washington Department of Natural Resources 1999, Battelle et al. in review). Loss of over 70 percent of Puget Sound coastal wetlands and estuaries to urban or agricultural development (diking, dredging, and hydromodification) has resulted in a massive reduction in potential rearing habitat for juvenile salmonids.

Longterm monitoring databases and historic inventories are generally inadequate to assess and evaluate nearshore habitat and resource trends in Washington State. However, some excellent data sets and maps (i.e., WDNR 2000, ShoreZone Inventory database) have been developed that provide a baseline inventory of current shoreline and intertidal habitat conditions throughout Puget Sound (Berry et al. 2001).

A preponderance of evidence exists to link the effects of shoreline modifications to changes in nearshore biological functions, although this evidence is primarily drawn from an inference-based conceptual understanding of nearshore ecosystem processes. Shoreline modifications exert effects at varying degrees on an ecosystem's controlling factors (e.g., water depth, substrate type, light level, and wave energy). Impacts that affect controlling factors within an ecosystem may be reflected in changes to habitat structure, and ultimately may be manifested as changes to functions supported by the habitat. For example, the composition of benthic substrate in nearshore marine and estuarine habitats are linked to local physical conditions and greatly influences biological resource functional benefits. A number of documents summarize the physical factors controlling habitat structure (Dethier et al. 1990), and the relationship between "natural" (predevelopment) estuarine and nearshore habitats and major aquatic resources in Washington State (Simenstad et al. 1991a).

Other shoreline or nearshore structures, such as tide gates, sewer outfalls, and artificial reefs, can impact nearshore marine and estuarine ecosystems in a variety of ways. Tide gates cause restricted movement of fish and materials and may degrade water quality in important aquatic habitats. Artificial reefs do effectively attract fish, but they may be a population sink rather than a source of new fish production; these fish aggregations may include predators of juvenile salmon. Outfalls essentially act as reefs that support a hard bottom community, and in the nearshore may impact hydrology and sediment transport processes.

Shoreline modification and restoration can have direct, indirect and cumulative impacts to estuarine and nearshore marine biological resources at a site, as well as in areas well beyond the location of the modifications. Effects appear to be highly site, habitat, and scale-dependent, and depend upon the level of disturbance and the relative sensitivity of the habitat to the disturbance. It is difficult to accurately generalize a finding from one site to another site. From a landscape perspective, the cumulative impact of losses in connectivity between natural nearshore and estuarine habitats remains difficult to measure and untested.

Research examining impacts of shoreline modification in the North Pacific coastal zone has primarily been in the form of observational studies of large structures with the highest impact *potential (jetties, harbors, breakwaters, or bulkheads).* In the Pacific Northwest most of this work has been directed at bulkheads or riprapped habitats, whereas none has examined marine revetments or groins. Furthermore, much of this work has concentrated on Puget Sound or Hood Canal, while no studies have been conducted on Washington's outer coast. These trends are likely a reflection of Washington's population distribution around Puget Sound, combined with the geomorphology of the region's shorelines.

Relatively little controlled research has been directed at documenting and understanding the functional impacts of shoreline modifications to biological resources. Few studies have applied rigorous, hypothesis-based testing that confirm these impacts. Most of the data gaps highlighted in previous reviews of the subject remain, with little actual research undertaken in the 20 years hence to clarify these questions.

Our basic understanding of nearshore ecosystem functions is often characterized by significant data gaps. For example, marine riparian vegetation appears to play an extremely important role in the nearshore ecosystem, but these functions are neither well documented nor protected. As a result, the related roles of LWD, shading, organic matter production and recruitment, sediment filtration, and microclimates in the survival and growth of juvenile salmonids and other nearshore-dependent species have not been well defined.

The best way to protect sensitive shoreline habitats is to avoid construction in and around these areas. Modifications to upland, riparian, estuarine, and marine shoreline habitats may affect areas both adjacent to and far removed from the immediate site of impact. The cumulative effects of many small modifications also have the potential to produce interactive or synergistic impacts, rather than merely additive impacts, although this remains untested.

The design and location of shoreline structures can significantly affect relative impacts to nearshore biological resources. For example, seawalls and bulkheads with solid vertical surfaces (e.g., concrete, steel) built waterward of MHW may have greater impacts on shoreline biological processes than gradually sloping, rock riprap revetments built above MHW.

Alternatives to hard shoreline armoring, such as beach nourishment and marine riparian vegetation enhancement, use natural materials and may often be the preferred alternative to minimize damage to habitats and resources. There is a need to systematically examine the long-term success or relative benefits these natural shoreline components accrue as habitat to nearshore species.

Properly designed estuarine restoration projects can return a habitat to a close approximation of its condition prior to disturbance. However, restoration actions vary widely in their "success" rate. The potential for success varies depending on the degree of disturbance that exists at the site and within the landscape where the restoration site is located. In addition, the process of restoring a site may have associated negative impacts in the short term.

Recommendations

While our review of the available research literature shows that explicit documention is limited, adequate evidence exists to suggest that shoreline modifications have a high potential for severely impacting nearshore biological resources in Washington State. Accordingly, we recommend that a comprehensive strategy be developed to better protect, restore, and enhance associated nearshore and estuarine habitats in the region. This strategy should be guided by existing datasets and inventories, with achievable goals that are periodically evaluated using an adaptive management framework. Simultaneously, a research and monitoring/assessment program must be undertaken to identify and fill critical data gaps to better understand nearshore biological functions and restoration needs, with an emphasis on how changes in habitat opportunity or capacity affect biological resources at a landscape scale. To achieve these ends, the following specific recommendations are offered:

A thorough physical assessment on a site-specific basis must be carried out to fully understand and document the potential direct, indirect and cumulative impacts prior to allowance of any shoreline modifications. Evaluations of potential effects of proposed shoreline modifications for a region must consider carefully how these functions will be affected prior to allowance of any modifications to take place. The assessment must be site-specific and scientifically rigorous enough to fully document the need for the modification, balanced by potential (including cumulative) impacts. Measures for protecting critical habitats must incorporate principles of landscape connectivity and extend to activities outside of their conveniently defined boundaries. When definitive scientific information is lacking but potential impacts are likely to occur, regulatory agencies should err on the side of caution to reach conservative decisions that favor natural, ecological functions.

Protect and restore sensitive marine nearshore and estuarine habitat and ecological functions by avoiding shoreline structural modifications altogether. Protection and conservation of ecologically important natural areas must be prioritized from a landscape perspective, especially those sites recognized for their importance to shoreline processes (e.g., sediment dynamics) and biological functions (e.g., fish migratory corridors or spawning and nursery habitats).

Where new shoreline modifications must occur, impacts should be minimized by pursuing alternative techniques (e.g., beach nourishment) and placement strategies. Advantages of alternative shoreline armoring techniques and guidelines for implementing them should be published in an easy to read format and distributed to shoreline property owners. Tide gates should be designed to minimize restrictions while affording flood protection. Manually-operated, latched, or self-regulated tide gates should be used in conjunction with culverts that maintain natural estuarine processes and afford passage (both upstream and downstream) to fishes during most flow events. Where possible, wastewater should be recycled and reused in upland areas to minimize the impacts of outfalls on the marine environment.

Phased restoration of natural processes and ecological functions should be achieved through the strategic removal of unnecessary shoreline structures, especially in areas with particularly high *rates of shoreline armoring and habitat structural modification.* Restoration project planning must be complete and include a site assessment to assure that the site is as correct as possible for the type of restoration planned and that any modifications needed to correct problems with the site are fully understood and carried out. Restoration is intended to result in a net benefit to the ecosystem, but restoration actions should be considered relative to the potential for success in order to maximize the net benefits.

Restoration projects are uncertain and must be planned and evaluated carefully. Site assessments to evaluate the suitability of a site for restoration must be conducted. This can include small-scale experiments that test the ability of selected plants to grow at the site. Experiments can be incorporated directly into restoration projects to test factors that may be important in the long-term development of the site. Control of undesirable species, as well as herbivores and predators, should be considered and implemented as needed. All restoration projects should be monitored under an adaptive management program that allows for adjustment of the site or goals during system development. This will greatly improve the probability of success of the project.

Existing documents (Dethier et al. 1990, Simenstad et al. 1991a) should be used to provide a solid scientific basis for assessing the potential effects of changes caused by shoreline modifications and restoration on habitats and resources. It is further recommended that these documents be periodically reviewed and updated on a regular schedule with new information.

Existing baseline inventories (e.g., WDNR 2000, ShoreZone Inventory database) should be used for determining habitat trends, locating critical areas for protection or restoration, and identifying nearshore ecosystems most at risk to cumulative impacts. Maps of a similar type should be developed and updated for all marine and estuarine shorelines in the state.

Key Research Needs

A comprehensive research program is needed immediately to provide critical empirical data required to understand the relationships between placement of artificial structures in the marine environment and direct, indirect, and cumulative physical and biological changes that will occur on a local and larger scale. Only from this type of effort can effective and meaningful guidance be developed that is comprehensive and defensible, considering the wide array of conditions where artificial structures might be placed. Our observations suggest that most of the data gaps highlighted by previous reviews (Mulvihill et al. 1980, Simenstad et al. 1991b, Macdonald et al. 1994, Thom et al. 1994a, Kahler et al. 2000) remain, with few research efforts undertaken in the 20+ years hence to rectify these oversights. Accordingly, many of our research recommendations parallel those made by previous authors.

The comprehensive study should include at least the following elements:

- Systematic monitoring studies of existing sites paired with matched, natural reference sites

- Direct documentation of ecological effects associated with physical changes, both before and after impacts occur

- Controlled experimental studies to compare existing or new technologies

- Cumulative effects of shoreline armoring on systems as a whole

- Importance of linkages between watersheds, uplands, and nearshore.

Maps and aerial photos are an existing tool for determining broad patterns in baseline conditions, but more directed onsite sampling and inventory is needed to evaluate many other habitat trends. Baseline monitoring and research into understanding basic system functions are integral components in any restoration plan. An understanding of existing conditions and natural/historic conditions is needed before we can expect to set goals for improvement.

Understanding the interconnectedness of nearshore habitat elements to the watersheds and marine environment is critical to recognizing their importance in the maintenance of biological diversity in the region. Functions of marine riparian vegetation need to be better documented in the scientific literature in order to create adequate policies for protection (e.g., functional buffer widths) and restoration. Likewise, the role of artificial reefs as population sinks or sources for those species associated with them should be clarified before these structures are recommended as management tools. Experimental research conducted now will allow us to fill knowledge gaps, learn from our actions, and minimize repetition of failures and wasteful expenditure of resources.

Long-term multi-site studies investigating residence time, survival, and growth in disturbed and undisturbed systems are needed to determine how highly modified environments affect salmonid populations, and the capacity of these habitats to support juvenile salmon. There have been no definitive studies investigating the effects of armoring on juvenile salmon feeding opportunities. While armored habitats have been found to provide suitable habitat for some forms of epibenthos that are known prey of juvenile salmonids, the ecological significance of different epibenthic communities to salmonids has not been studied. Neither have there been quantitative studies investigating the effects of shoreline armoring and associated shoreline steepening on the vulnerability of juvenile salmonids to predation. Existing data are qualitative, observational, or anecdotal.

A database, similar to that developed for eelgrass restoration projects in California, should be maintained for all estuarine and nearshore restoration and monitoring projects in the state. Restoration projects must be monitored and the information should be systematically reported. This information should be available widely and include information on the design, goals, performance criteria, construction, monitoring and management of the systems. The database could be maintained as part of the existing Puget Sound Ambient Monitoring Program (PSAMP), which is coordinated through the Puget Sound Water Quality Action Team (see http://www.wa.gov/puget_sound/Programs/PSAMP.htm).

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APPENDIX A

Washington State Marine and Estuarine Habitat Classification System (Dethier 1990)

Estuarine Habitat Classification System

Summary of Washington State habitat classification scheme for marine and estuarine habitats (Dethier 1990) .

SYSTEM	SUBSTRATE	WAVE ENERGY	DEPTH	PLANTS
Marine-intertidal Estuarine-intertidal	rock	exposed, partially exposed semi-protected	eulittoral	rockweed, algae, kelps, surfgrass
	rock	all exposures	backshore	algae
	cobble	partially exposed		algae
	mixed-coarse	semi-protected exposed		seasonal drift algae
	gravel	partially exposed		none
	gravel	semi-protected		algae
	sand	exposed, partially exposed		none
	sand	semi-protected, protected		eelgrass, algae
	mixed-fines	semi-protected, protected		eelgrass, algae
	mud	protected		eelgrass, algae
Marine-subtidal	mixed-coarse	mod to low energy	shallow	surfgrass, eelgrass, algae
	gravel	high energy	shallow	
	mixed-fines	moderate to high energy	shallow	algae
	mud, mixed-fines	low energy	shallow	algae
Estuarine-intertidal	mixed-coarse	open	eulittoral	algae; often eelgrass beds lie just subtidally of these beaches
	gravel	partly enclosed	eulittoral (marsh)	pickleweed, saltwort, rockweed
	sand	open	open	eelgrass, gracilaria
	sand, mixed fines, mud	partly enclosed lagoon	eulittoral (marsh)	vascular plants, bulrush, sedge, pickleweed (depending on salinity)
	mud	partly enclosed, enclosed		eelgrass
	organic, sand, mixed-fines mud	partly closed, partly enclosed	backshore (marsh)	sedge, grasses, vascular plant (species depending on salinity), high marsh plants
	mixed-fines, mud	channel/slough		eelgrass, lined with marsh plants
Estuarine-subtidal	rock, cobble	open	shallow	algae
	sand	open	shallow	eelgrass
	mixed-fines	open	shallow	eelgrass, algae, kelp
	mud	open	shallow	eelgrass, algae
	mud	partly enclosed	shallow	
	sand, mud	channels		

APPENDIX B

Estuarine Habitat Assessment Protocol Species Matrix (Simenstad et al. 1991a)

Table B1. Habitat-specific table of species assemblages in Puget Sound estuaries (Simenstad et al. 1991, adapted from Thom et al. 1994).

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 trunstone				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							

Table B1. Habitat-specific table of species assemblages in Puget Sound estuaries (Simenstad et al. 1991, adapted from Thom et al. 1994) (continued).

NO.	GROUP	SPECIES	EMER. MARSH	MUDFLAT	SANDFLAT	GRAV.-COB.	EELGR.	SUBT. SOFT	SUBT. HARD	WAT. COL.
28	Birds	osprey	■				■			■
29	Birds	red-breasted merganser								■
30	Birds	red-tailed hawk	■							
31	Birds	redwing blackbird	■							
32	Birds	savannah sparrow	■							
33	Birds	short-billed dowitcher	■	■						
34	Birds	short-eared owl	■							
35	Birds	song sparrow	■							
36	Birds	spotted sandpiper	■	■	■	■	■			
37	Birds	Virginia rail	■							
38	Birds	western grebe				■				■
39	Birds	western sandpiper	■	■						
40	Fish	bay goby		■	■					
41	Fish	bay pipefish					■			
42	Fish	black rockfish							■	
43	Fish	brown rockfish							■	
44	Fish	buffalo sculpin				■				
45	Fish	cabezon							■	
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						■		

Table B1. Habitat-specific table of species assemblages in Puget Sound estuaries (Simenstad et al. 1991, adapted from Thom et al. 1994) (continued).

NO.	GROUP	SPECIES	*EMER. MARSH*	*MUDFLAT*	*SANDFLAT*	*GRAV.-COB.*	*EELGR.*	*SUBT. SOFT*	*SUBT. HARD*	*WAT. COL.*
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 anchovie								■
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						■		

Table B1. Habitat-specific table of species assemblages in Puget Sound estuaries (Simenstad et al. 1991, adapted from Thom et al. 1994) (continued).

NO.	GROUP	SPECIES	*EMER. MARSH*	*MUDFLAT*	*SANDFLAT*	*GRAV.-COB.*	*EELGR.*	*SUBT. SOFT*	*SUBT. HARD*	*WAT. COL.*
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 trout								■
89	Fish	striped seaperch					■		■	
90	Fish	sturgeon poacher						■		
91	Fish	surf smelt				■				■
92	Fish	threespine stickleback	■							■
93	Fish	tube-snout					■			
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	■							

APPENDIX C

Glossary of Terms

Glossary of Terms

ABIOTIC
The non-living factors of a given area, such as temperature, wind, substrate, etc.
ACCRETION
May be either natural or artificial. Natural accretion is the buildup of land, solely by the action of the forces of nature, on a beach by deposition of water- or airborne material. Artificial accretion is a similar buildup of land by reason of an act of man, such as the accretion formed by a groin, breakwater, or beach fill deposited by mechanical means.
AERIAL
Portion of a plant that remains above the soil surface, such as the leaves.
ALONGSHORE
Parallel to and near the shoreline. (LONGSHORE)
ANADROMOUS
Fish that reproduce in fresh water, but spend a portion of their life in salt water.
ARMORING
Physical modifications to the shoreline implemented by man. See HARDENING.
ARTIFICIAL REEF
A man-made structure designed to simulate a natural reef.
ASSEMBLAGE
The group of species generally associated with a given habitat type.
BACKFILL
Material used to fill behind a small structure such as a seawall or bulkhead. Also, the act of placing material behind a small structure such as a seawall or bulkhead.
BACKSHORE
Zone of beach lying between foreshore and coastline acted upon by waves only during severe storms.
BACKSIDE EROSION
Erosion of the material behind a structure such as a bulkhead or seawall. Usually caused by wave overtopping or runoff.
BAITFISH
Group of fish that are important to salmonids as food fish.
BAR
A submerged or emerged embankment of sand, gravel, or other unconsolidated material built on the sea floor in shallow water by waves and currents.
BATHYMETRY
The measurement of depths of water in oceans, seas, and lakes. Also, information derived from such measurements.
BEACH GRADIENT
The angle of the beach down the beach profile, as it extends seaward.
BEACH PROFILE
A vertical cross section of a beach measured perpendicular to the shoreline.
BENTHOS
Organisms growing on or associated principally with the water bottom. (BENTHIC)

BERM
Nearly horizontal part of beach or backshore formed of material deposited by wave action.
BIOPHYSICAL
The biological and physical attributes of an ecosystem.
BIOTA
The animal and plant life of a region.
BIOTECHNICAL
Method of shoreline stabilization that utilizes vegetation to enhance slope stability and resist erosion.
BORROW PIT
Dredged area that supplies the sediment for a nourishment project.
BREACHING
The breaking of a dike to form a channel. May be natural or caused by man.
BREAKER ZONE
Zone of shoreline where waves break.
BREAKWATER
Structure protecting shore area, harbor, anchorage, or basin from waves. See JETTY.
BULKHEAD - Structure or partition built to prevent sliding of the land behind it. It is normally vertical or consists of a series of vertical sections stepped back from the water. A bulkhead is ordinarily built parallel or nearly parallel to the shoreline.
CAPPING
Covering up of contaminated sediment in order to prevent toxic release into the environment.
CHANNEL
A natural or artificial waterway of perceptible extent which either periodically or continuously contains moving water, or which forms a connecting link between two bodies of water.
COMMUNITY
Association of plants and/or animals in a given area or region in which various species are more or less dependent upon each other.
CONTOUR WATTLING
Method of slope stabilization that involves the use of wrapped vegetation bundles along the contour of a face, in order to facilitate lateral water runoff and reduce downcutting.
CREST
The seaward limit of a berm. Also, the highest part of a wave.
CROSS-SHORE
Sediment travel up or down the profile of a beach.
CULVERT
Man-made structure placed to enhance water flow-through in an area, generally a pipe.
CURRENT
A flow of water.
DEFLATION
The removal of loose material from a beach or other land surface by wind action.
DEPOSITION
The deposit of sediment in an area through natural means such as wave action or currents; may also be done by man through mechanical means.

DESSICATION
Critical loss of fluids; drying out.

DIKE
Wall or mound built around low-lying area to control flooding.

DISPHOTIC ZONE
The region of water below the euphotic zone, that receives low levels of light, but not enough for photosynthesis

DISTRIBUTARY CHANNEL
A channel that flows off of and away from the main channel, which does not rejoin.

DISTURBANCE
Any natural or man-caused impact to an ecosystem.

DOWNCUT
Large channel down the slope of a face, caused by heavy runoff.

DOWNDRIFT
The direction of predominant movement of littoral materials.

DREDGE
To deepen by removing substrate material. Also, mechanical or hydraulic equipment used for excavation.

DRIFT SECTOR
A segment of shoreline along which littoral, or longshore, sediment movement occurs at noticeable rates. It allows for an uninterrupted movement, or drift, of beach materials. Each drift sector includes: a feed source that supplied the sediment, a driftway along which the sediment can move, an accretion terminal where the drift material is deposited, and boundaries that delineate the end of the drift sector. (Also called a DRIFT CELL or LITTORAL CELL)

ECOSYSTEM
The organization of all biotic and abiotic factors in an area, usually delineated by natural geographic barriers.

EMBANKMENT
Artificial bank such as a mound or dike, generally built to hold back water or to carry a roadway.

ENCRUSTING BIOTA
Animal or plant life that attaches itself to a given substrate or object, such as a barnacle or mussel.

EPIBENTHOS
Organisms that live on the surface of the bottom sediment. (EPIBENTHIC)

EROSION
The wearing away of land by natural forces. On a beach, the carrying away of beach material by wave action, tidal currents, littoral currents, or by deflation.

ESTUARY
Region near river mouth where fresh water mixes with salt water of sea. (ESTUARINE)

EUPHOTIC ZONE
The surface waters of the oceans that receive sufficient light for photosynthesis to occur.

EUTROPHICATION
The gradual process whereby lakes accumulate excessive nutrients, eventually resulting in low levels of dissolved oxygen and suffocation of the resident biota.

FACE
The front or exposed area of a slope or structure.

FETCH
The distance over unobstructed open water on which waves are generated by a wind having a constant direction and speed.

FLANKING
Wave action around the top or sides of a structure.

FORESHORE
Part of the shore lying between crest of seaward berm and ordinary low water mark.

GABION
Hollow cylinder or wire mesh basket filled with earth or stone, used to build revetments.

GEOMORPHOLOGY
The shape or form of a natural surface or object. Also, the study of the forms of the land surface and the processes producing them.

GROIN
A rigid structure built at an angle (usually perpendicular) from the shore to protect it from erosion or to trap sand. A groin may be further defined as permeable or impermeable depending on whether or not it is designed to pass sand through it.

GROUNDWATER - Underground water supplies, also called aquifers. Water soaks into the ground until it reaches a point where the ground is not permeable. Ground water usually then flows laterally toward a river or lake, or the ocean.

HABITAT
Interacting physical and biological factors which provide at least minimal conditions for one organism to live or for a group of organisms to occur together.

HARDENING
(See ARMORING)

HYDRAULIC
Of or pertaining to water.

HYDROLOGY
The dynamics of water movement through an area.

HYDROSTATIC PRESSURE
Pressure in a system from water collection, may be gravitational or chemical.

IMPACT
An action producing a significant causal effect or the whole or part of a given phenomenon.

IMPOUNDMENT
The retention or trapping of sediment in a location, either by natural or structural means.

INFAUNA
Organisms that live within the sediment.

INFILTRATION
Water flow into the soil to replenish aquifers.

INTERSPECIFIC COMPETITION
Competition for resources between different species.

INTERTIDAL
The area between high and low tides, which is uncovered periodically.

INVERTEBRATES
Animals that lack a bony or cartilaginous skeletal structure.

JETTY
Structure extending into body of water designed to prevent shoaling of channel by littoral materials and to direct or confine stream or tidal flow.

LWD
Large woody debris.

LEE-SIDE
The side of a structure protected from wind or wave action.

LITTORAL
Of or pertaining to the shore

MACROFAUNA
Organisms in a particular ecosystem that are of a visible size.

MACROINVERTEBRATES
Invertebrates that are of visible size, such as clams and worms.

MARINE
Water that contains high salt content, as opposed to freshwater.

MARSH
An area of soft, wet, or periodically inundated land, generally treeless and usually characterized by grasses and other low growth.

MEAN HIGH WATER
Average height of high waters over a 19-yr period.

MEAN LOW WATER
Average height of low waters over a 19-yr period.

MICROCLIMATE
The climate generally observed in a small, specific region such as an estuary or under a rock.

MIGRATION
The seasonal travel of an animal between habitats.

MIGRATORY CORRIDOR
The physical pathway through which animals migrate.

MUDFLAT
Low, unvegetated mud substrate that is flooded at high tide and uncovered at low tide.

NEARSHORE
In beach terminology an indefinite zone extending seaward from the shoreline well beyond the breaker zone.

NOURISHMENT
Process of replenishing a beach; naturally by longshore transport or artificially by deposition of dredged material. (BEACH NOURISHMENT)

OUTFALL
Structure extending into a body of water for the purpose of discharging an effluent (sewage, storm runoff, cooling water).

OUTMIGRATION
Refers to the act of anadromous salmonids when leaving freshwater and migrating to the sea for part of their life.

OVERWATER STRUCTURES
Man-made structures that extend over all or part of the surface of a body of water, such as a pier.

OVERTOPPING
Passing of water over the top of a structure as a result of wave runup or surge action.

OVERWASH
That portion of the uprush that carries over the crest of a berm or of a structure.

PARTICLE BINDING
Stabilization of soil particles through natural mechanisms such as root-wad formation, reducing the potential of loss through wind or water erosion.

PHOTIC ZONE
The surface waters of the ocean that receive light. Includes the euphotic and disphotic zones.

PHYSICOCHEMICAL
The physical and chemical properties of water.

PILE
Long, heavy timber or section of concrete or metal driven or jetted into earth or seabed for support or protection.

PILING
Group of piles.

PLANKTON
Suspended microorganisms with relatively little power of locomotion that drift in water and are subject to action of waves or currents.

PONDING BASIN
Area designed to trap water runoff and allow it to drain at stable rate.

RAMP
A uniformly sloping platform, walkway, or driveway. The ramp commonly seen in the coastal environment is the launching ramp, which is a sloping platform for launching small craft.

REEF
An offshore chain or ridge of rock or ridge of sand at or near the surface of the water.

REFUGE
Habitat area that provides protection from predators or disturbance.

RELIEF
The elevational features of a surface.

REMINERALIZE
Process through which nutrients are broken down into their original inorganic structure, and are made available for biological use.

RENOURISHMENT
The follow-up nourishment of a beach nourishment or fill project, often required in high-energy areas with rapid erosion.

RETAINING WALL
Wall built to keep bank of earth from sliding or water from flooding. See BULKHEAD.

REVETMENT
: A sloped facing built to protect existing land or newly created embankments against erosion by wave action, currents, or weather. Revetments are usually placed parallel to the natural shoreline.

RILL
: Tiny drainage channel in a beach caused by seaward flow of water.

RIP CURRENT
: A strong surface current flowing seaward from the shore.

RIPARIAN
: Pertaining to the banks of a body of water.

RIPRAP
: Layer, facing, or protective mound of stones randomly placed to prevent erosion, scour, or sloughing of structure or embankment. See REVETMENT.

RUBBLE
: Rough, irregular fragments of broken rock.

RUBBLE-MOUND STRUCTURE
: Mound of random-shaped and random-placed stones protected with cover layer of stones or specially shaped concrete armor units.

RUNUP
: The rush of water up a structure or beach on the breaking of a wave. (UPRUSH, SWASH)

SALINITY
: A measure of the concentration of dissolved salts in water, usually expressed as parts per thousand (ppt.)

SANDFLAT
: Area extending from shoreline seaward that exhibits primarily sand substrate.

SCOUR
: The removal of underwater material by waves and currents, especially at base or toe of a structure.

SEAWALL
: Structure separating land and water areas, primarily designed to protect land from wave action.

SEDIMENT DYNAMICS
: The physical processes that sediment particles are subject to in an area, such as longshore drift.

SEEP
: Location where groundwater rises above the land surface, or exits the soil on a slope.

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

SHOALING
: Gradual procession from a greater to a lesser depth of water.

SHORELINE
: The intersection of a specified plane of water with the shore or beach.

SPATIAL PATCHINESS
: Refers to the clumped nature of biotic distribution in an ecosystem.

SPAWNING
Production and deposition of eggs, with reference to aquatic animals.

SPECIES RICHNESS
A metric used to compare the diversity of species among ecosystems, indicative of variety.

SUBAERIAL WETLAND
Wetlands that occur landward of the general salt-water shoreline -- excludes intertidal wetlands.

SUBSTRATE
Solid material upon which an organism lives or to which it is attached.

SUBTIDAL
The marine environment below low tide.

SURF ZONE
The area between the outermost breaker and the limit of wave uprush.

SURFACE WATER
Water that travels across the surface of the ground, rather than infiltrating.

TERRESTRIAL
Growing or living on or peculiar to the land, as opposed to the aquatic environment.

TIDAL FLAT
The sea bottom, usually wide, flat, muddy, and unvegetated which is exposed at low tide; marshy or muddy area that is covered and uncovered by the rise and fall of the tide.

TIDAL PRISM
The total amount of water that flows into a harbor or estuary or out again with movement of the tide, excluding any freshwater flow.

TIDE GATE
An opening through which water may flow freely when the tide or water level is low or high, but which will be closed to prevent water from flowing in the other direction when the water level changes.

TOE
The lowest part of a bluff, bank, or shoreline structure, where a steeply sloping face meets the beach.

TOPOGRAPHY
The configuration of a surface, including its relief and the positions of its streams, roads, buildings, etc.

TRAINING WALL
A wall or jetty to direct current flow.

TRANSPORT
The movement of sediment along a current pathway.

TURBIDITY
A measure of the clarity of water, indicating quantities of suspended material. Higher turbidity results in lower levels of light penetration throughout the water column.

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

UPLANDS
The land above a shoreline.

WATER COLUMN
: The water in a lake, estuary, or ocean which extends from the bottom sediments to the water surface.

WAVE CLIMATE
: Annual and seasonal conditions that characterize the wave activity in a particular region.

WAVE ENERGY
: Force exhibited by waves, which culminates in impact to an object or surface.

WEIR JETTY
: An updrift jetty with a low section or weir over which littoral drift moves into a pre-dredged deposition basin which is periodically dredged.

WETLANDS
: Lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water.

APPENDIX D

Other Sources of Information and Material Availability

Other Sources of Information and Material Availability

Most resources are available at UW libraries or the government agency that published the document. Exceptions are:

- Canning and Shipman 1993. Shipman and Canning 1993. - contact American Society of Civil Engineers - http://www.asce.org, marketing@asce.org, 1-800-548-ASCE
- Kahler 2000. - contact Watershed Co., email - watershed@watershedco.com
- Thom and Borde 1998. - request from NOAA, email - coastalocean@cop.noaa.gov
- Shipman, Stoops, and Hummel 2000. – unpublished notes, personal. communication.

Agency Contact/Publications Request Info:

- Washington Department of Ecology - http://www.ecy.gov, ecypub@ecy.wa.gov, 360/ 407-7472
- Washington State Dept. of Fish and Wildlife - http://www.wa.gov/wdfw, 360/ 902-2200
- Puget Sound Water Quality Authority/ Action Team - http://www.wa.gov/puget_sound/Publications/Publications.htm
- U.S. Army Corps of Engineers (WES) - http://bigfoot.wes.army.mil/c133/html
- EPA - http://www.epa.gov/epahome/publications.htm