Marine Riparian:
An Assessment of Riparian Functions in Marine Ecosystems

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An Assessment of Riparian Functions
In Marine Ecosystems

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Executive Summary

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While marine nearshore environments are some of the most resource-rich and economically important ecosystems in the world, the structure, functions, and processes that form and maintain habitats in these systems are complex and poorly understood. Of the many habitats constituting the nearshore, perhaps the least understood and most unappreciated, in terms of critical functions, are riparian areas. Riparian areas have been studied intensely in recent years because of their critical functional relationships to stream and freshwater wetland ecosystems. Marine riparian areas, on the other hand, have received little attention. Although marine riparian systems have not been subject to the same level of scientific investigation, a growing body of evidence suggests that riparian systems serve similar functions regardless of the salinity of the water bodies they border. While riparian areas and shoreline vegetation have been identified as integral and important parts of the marine nearshore ecosystem, their functions and benefits have not been adequately evaluated and integrated into shoreline management strategies. Recognizing this gap in our knowledge and the apparent links between shoreline vegetation and the nearshore ecosystem based on personal observations, we began an investigation with a preliminary review of the scientific literature and interviews with other marine scientists. Our working hypothesis is that marine riparian systems provide functions similar to those described for freshwater riparian systems and are likely to provide additional functions unique to marine nearshore ecosystems. Following this preliminary assessment, we conducted a more extensive literature review and assessment of riparian functions relative to marine systems.

In this paper, we review riparian functions and associated benefits (i.e., ecological or social values) as they relate to the marine environment, using the most commonly reviewed freshwater riparian function topics as a template. The functions reviewed for this paper include water quality, soil stability, sediment control, wildlife habitat, microclimate, nutrient input, fish prey production, shade, and habitat structure with an emphasis on large woody debris (LWD). We also briefly review and discuss social values such as human health and safety, and aesthetics. In addition, we assess the relationship between current regulatory and management strategies and their effectiveness in protecting riparian and marine resources and the ecosystem as a whole. In addition to presenting the above-stated reviews and assessments, we provide a foundation to enhance discussions of shoreline management and improve resource protection through an increased understanding of nearshore and marine riparian ecosystems.

Marine Riparian Functions

Water Quality: Degradation of urban waterways is directly linked to urbanization and has been exacerbated by the lack of adequate storage, treatment, and filtration mechanisms for runoff. Water collected in stormwater systems, sewage, and discharges from industrial sources may or may not be treated and contains varying levels of silt, waste, and chemical constituents that could otherwise be absorbed or removed by allowing for infiltration, detention, and absorption by soils and vegetation. The use of riparian areas for pollution abatement is well documented and vegetated buffers are known to be efficient and cost effective. However, determining appropriate buffer widths to provide pollution abatement functions will require some basic knowledge of environmental conditions.

Soil Stability: Vegetation affects both the surficial and mass stability of slopes in significant and important ways, ranging from mechanical reinforcement and restraint by the roots and stems to modification of slope hydrology as a result of soil moisture extraction via evapotranspiration. Vegetation, once established, provides a self-perpetuating and increasingly effective permanent erosion control. Soils, slope height and angle, drainage, and other factors are also very important in determining susceptibility to erosion. For shorelines, and particularly those in areas with steep and eroding bluffs, native vegetation is usually the best tool for keeping the bluff intact and for minimizing erosion. Removal of the vegetation that helps to stabilize the face, or excavation along the face, increases the chance of slumping, which results in imperiled structures, lost land, a disruption to the ecological edge-zone, and increased sedimentation to the aquatic environment.

Sediment Control: The control of sediments entering waterways is one of the most commonly identified functions of riparian areas in freshwater and coastal riparian studies. Most discussions of sediment control are addressed in the context of functional mechanisms of pollution abatement and soil stability provided by riparian buffers. In addition to the various pollutants associated with sediments, fine sediments can have a dramatic physical effect on aquatic organisms. Siltation can clog the breathing apparatus (i.e., gills) of fishes and invertebrates, inhibit proper respiratory function in eggs and larvae (suffocation), alter substrates, and bury benthic organisms. The inherent qualities of riparian vegetation to slow runoff, stabilize soils, take up nutrients and other contaminants, and reduce siltation are common knowledge and serve even greater functions in protecting water bodies from contamination.

Wildlife Habitat: Healthy (i.e., intact and functional) riparian systems along marine shorelines support abundant and diverse assemblages of wildlife. Of the 331 wildlife species known to inhabit all of King County, Washington, we identified 263 wildlife species (9 amphibians, 5 reptiles, 192 birds, 57 mammals) known or expected to be associated with marine riparian habitat. This represents 79.5% of all wildlife species found in King County. Many wildlife species are dependent upon riparian areas for their entire life cycle, with requirements for feeding, breeding, refuge, cover, movement, migration, and climate that are intricately interwoven into the ecological balance of riparian structure, functions, and processes. Other wildlife may only depend on riparian areas during a specific life stage, for limited periods during seasonal migrations, or simply as a migration corridor. Regardless of the timing, the availability and condition of riparian habitat can determine their survival, and many wildlife species have been extirpated due to the dramatic alteration and loss of marine riparian habitat.

Microclimate: Riparian plant and animal communities are greatly influenced by marine waters—especially those communities immediately adjacent to marine waters—through temperature and moisture regulation, tidal inundation, wind exposure, and salt spray. Marine littoral communities are, in turn, influenced by riparian conditions. The greatest influence of marine waters on riparian communities is temperature; marine waters keep lowland areas cooler in the summer and warmer in the winter. Temperature and moisture are also regulated by the amount of vegetative cover on the land. Together, these factors contribute to microclimates upon which fish and wildlife depend. Removing vegetation in upland and riparian areas increases exposure of the land and water to sun and decreases organic matter, resulting in elevated runoff and increased temperatures for water entering marine systems, desiccation of soils, and increased stress for animals dependent upon cool, moist conditions.

Shade: Solar radiation (which leads to increased temperatures and desiccation) has long been recognized as one of the classic limiting factors for upper intertidal organisms and plays an important role in determining distribution, abundance, and species composition. Although the influence and importance of shade derived from shoreline vegetation in the Puget Sound nearshore ecosystem is not well understood, it is recognized as a limiting factor to be considered and has prompted investigations to determine direct linkages between riparian vegetation and marine organisms. One such link is the relationship between shade and surf smelt (*Hypomesus pretiosus*), a common nearshore forage fish found throughout the Puget Sound basin. On the basis of a comparison of adjacent shaded and unshaded spawning sites sampled in northern Puget Sound, Penttila (2001) found significantly higher egg mortality on the unshaded (sun-exposed) beaches. Considering the influences of temperature, moisture, and exposure on the diversity, distribution, and abundance of organisms that use upper intertidal zones, additional benefits of natural shading likely will be discovered as we investigate further.

Nutrient Inputs: One of the characteristics that makes marine nearshore areas so productive is that they act as sinks for nutrients derived from upland and marine sources. The primary source of nutrients in the system is derived from primary producers (i.e., aquatic and terrestrial vegetation, phytoplankton), although terrestrial-derived organic contributions have not been well studied. Alterations of intertidal and subtidal areas by dredging, filling, diking, overwater structures, and shoreline armoring have dramatically affected marine wetland and other aquatic vegetation (i.e., eelgrass, algae). Similarly, upland development has greatly reduced the amount of vegetation and nutrients available to the marine system. Such modifications have resulted in decreased abundance and taxa richness in both benthic and infaunal invertebrate and insect assemblages.

Fish Prey Production: Of the dietary studies of marine fishes that were reviewed for this study, it appears that salmon benefit most from riparian vegetation. For those species of salmonids (i.e., cutthroat trout, chinook and chum salmon) known to be most dependent upon shallow, nearshore waters, insects derived from the terrestrial environment appear to play an important role in their diets. Because of limited sampling and dietary analysis of juvenile salmonids and other fishes in the nearshore environment, we need additional studies to understand the contribution of riparian vegetation to nearshore food webs and the impacts of vegetation loss along marine shorelines. However, as vegetation is eliminated, the food supply, and thus the carrying capacity of the coastal ecosystem, is likely to be reduced.

Habitat Structure/LWD: Riparian vegetation and large woody debris (LWD) provide a multitude of functions in aquatic ecosystems and riparian forests. One primary role of vegetation and LWD is habitat structure. The role and importance of LWD in freshwater lotic systems has been well documented and has led to increasing efforts to use LWD for bank stabilization and habitat restoration. Course woody debris is also an important part of estuarine and oceanic habitats, from upper tidewater of coastal rivers to the open ocean surface and the deep sea floor. The ecological functions of riparian vegetation and LWD in the estuarine environment are much the same as those in freshwater systems, but many of the wildlife species, and most of the fish species that have direct and indirect dependency upon riparian functions are different. Structurally, LWD provides potential 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 and algae in the marine/estuarine environment. As the source of this material has diminished, so have the many functions provided to fish and wildlife.

Human Health and Safety: At least three riparian functions—water quality, soil stability, and the ability to act as a separation zone (i.e., absorb the impacts of storm surges and other natural, physical assaults on shorelines)—apparently serve direct benefits to humans, especially in areas like the Puget Sound region. In addition to heavy metals, petroleum, and other chemical constituents, pathogenic bacteria and viruses pose a serious health risk to humans. Shoreline erosion, landslides, and tidal inundation also pose threats to development along shorelines. Prohibiting buildings in slide-prone areas, establishing proper buffers and setbacks, controlling drainage, and maintaining native vegetation would greatly reduce hazards to humans and maintain ecosystem integrity.

Aesthetics: Aesthetic qualities are not physical or biological functions of riparian areas, but they are societal values. Aesthetic qualities of riparian areas enhance livability and add to the quality of life for residents and visitors and are of economic value for ecological functions and outdoor activities (e.g., wildlife viewing, boating, hiking).

Findings

This study focuses on riparian functions and marine ecosystem issues in the Puget Sound region. The lack of directed marine riparian studies in this region required a review and assessment of the national and international literature to determine whether studies performed in other coastal regions may be helpful in understanding the importance of individual riparian functions for Puget Sound. Our findings indicate that both freshwater and marine riparian systems serve almost identical purposes, and that marine riparian systems provide additional functions important for supporting marine biota and the integrity of nearshore ecosystems. Unfortunately, the lack of directed studies for defining the full suite of marine riparian functions and values in this region (and elsewhere) leaves much uncertainty and has resulted in a lack of standards and practices to protect riparian systems and other coastal resources.

The Puget Sound region has realized some of the most rapid coastal population growth in recent years and is expected to support continued growth in the coming decades. This will inevitably result in an increasing demand for shoreline development. Living right next to the water is highly valued in our society, but usually results in the clearing of native vegetation for view corridors, buildings, landscaping, and appurtenant structures such as bulkheads and docks. Unfortunately, shoreline development activities have significantly altered the natural structure, functions, processes, and beauty of our shorelines. Much of the historical destruction occurred without regard for the long-term consequences. Furthermore, science and public education have certainly not kept up with the level of development. However, despite the fact that current scientific knowledge and public sentiment support protection of natural resources for a variety of reasons, including aesthetics, existing environmental protection programs have proven to be woefully inadequate and ineffective at stopping the losses.

While research and empirical data to quantify functional characteristics of marine riparian systems in Puget Sound are substantially lacking, this review and assessment indicates that marine riparian functions play an important role in marine nearshore ecosystems. Our assessment also indicates that the lack of attention to marine riparian areas and poor protective standards have resulted in substantial loss and degradation of marine riparian and nearshore ecosystem components, which are of value to fishes, wildlife, and human health and safety. There is a critical need to develop and implement a research program and protective standards to learn more about marine riparian systems and prevent further degradation and loss of riparian functions and benefits.

Recommendations

The following recommendations should be considered as a part of any coastal management strategy and development of shoreline regulations.

Use the Precautionary Principle: "Do No Further Harm"
Preventing additional losses is both critical and cost effective. Once riparian functions are lost, they are difficult and expensive to restore, if restoration is possible at all.

Fill Data Gaps
The lack of empirical data for northwest coastal ecosystems and limited recognition of riparian functions has led to poor management practices and protection standards for coastal resources. Research and documentation are critical for establishing a scientific foundation for creating adequate policies and practices for protection and restoration.

Establish Appropriate Buffers and Setbacks
Buffers and setbacks are essential, functional and cost effective tools for preserving important processes and functions, preventing environmental degradation and protecting valuable coastal resources.

Maintain and/or Restore Riparian Vegetation for Human Health and Safety
Flooding, storm and erosion hazards are a common problem in coastal areas and become a greater threat when shoreline development does not consider the functions and values of maintaining riparian vegetation buffers (see Beatley et al. 1994; NRC 2002).

Identify, Evaluate and Incorporate Multiple Functions Into A Management Strategy
Any management strategy should be based upon maintaining all natural processes and functions, determined by an evaluation of the specific requirements for maintaining individual and collective functions over space and time (e.g., LWD recruitment; life history requirements of multiple species of fishes and wildlife).

Use a Multidisciplinary Approach in Developing Riparian Management Zones
Experts in a wide range of natural sciences should collaborate on an integrated and multidisciplinary assessment.

Maintain and/or Restore Riparian Vegetation for Pollution Abatement and Soil Stability
Vegetative buffers would likely be of benefit by reducing contaminants in runoff and reduce costly reactionary measures to clean up waterways.

Maintain and/or Restore Riparian Vegetation for Fish and Wildlife
It is clear that as vegetation is eliminated, the food supply, and thus the carrying capacity of the coastal ecosystem, is reduced.

Protect Marine Riparian Areas From Loss and Degradation
Riparian areas provide a wide range of functions, which are beneficial to humans, fish and wildlife. Every effort should be made to preserve remaining marine riparian areas from further degradation, fragmentation and loss.

Increase Public Education and Outreach
It is critical that decision-makers and the general public be educated about the outcomes of their actions, especially those that have the greatest influence on outcomes (i.e., those that live, work and play along our shorelines).

Develop and Implement Conservation Programs
Use ecological principles to guide actions and incorporate multiple functions and processes in developing goals and objectives for conservation actions.

Develop Incentives for Conservation Programs
Land acquisition, tax incentives, regulatory incentives and other measures have been used and should be considered in the development of conservation programs.

Introduction

While marine nearshore environments are some of the most resource-rich and economically important ecosystems in the world, the structure, functions, and processes that form and maintain habitat in these systems are complex and poorly understood. Of the many habitats constituting the nearshore, perhaps the least understood and most unappreciated, in terms of critical functions, are riparian areas. Riparian areas have been studied intensely in recent years because of their critical functional relationships to stream and wetland ecosystems. Marine riparian areas, on the other hand, have received little attention. As a result, most definitions of riparian systems are oriented to freshwater. In defining riparian systems, most authors omit any reference to tidal waters, which seems to be more of a reflection of the study area than a definition of the functional relationship (e.g., Gregory et al. 1991, Naiman et al. 1993). However, riparian areas are generally understood to be the interface between terrestrial and aquatic ecosystems. Therefore, early in the development of this manuscript (which began in 2001) we merged language used by Swanson et al. (1982) and Hall (1987) for a simplified definition that captures all aquatic systems. In order to be more inclusive, we initially defined riparian systems for this paper as follows: *Riparian systems are located in those areas that are on or by land bordering a wetland, stream, lake, tidewater, or other body of water, and which constitute the interface between terrestrial and aquatic ecosystems*. Subsequently, the National Research Council (NRC 2002) developed the following definition, which is largely in line with our original definition by recognizing marine riparian areas and we recommend using this definition:

> Riparian areas are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., zone of influence). Riparian areas are adjacent to perennial, intermittent, and ephemeral streams, lakes, and estuarine–marine shorelines (NRC 2002).

The interface of these two systems results in mutual influences and unique characteristics. In general, healthy riparian systems are defined by characteristics that may include some or all of the following:

- long linear shapes
- high edge-to-area ratios
- microclimates distinct from those of adjacent uplands
- standing or flowing water present all or much of the year, or a capacity to convey or retain water
- periodic flooding, which results in greater natural diversity
- composition of native vegetation differing somewhat from upland (inland) systems (e.g., different species abundance, diversity, and structure)
- support systems for terrestrial and aquatic biota

These characteristics create a unique environment (i.e., ecotone) that is complex, provides distinct functions not found in other ecotones, and typically supports higher species diversity and richness than non-riparian areas. While nested within and connected to other ecosystems within the landscape, riparian systems are themselves distinct ecosystems. Adjacent to marine waters, marine riparian systems are directly linked to, and are a part of, marine nearshore ecosystems owing to the mutual influences and dependencies upon similar processes and functional relationships.

Marine nearshore environments, particularly estuarine systems, are some of the most biologically productive and economically important systems in the world. As such, they are also among the most popular places for human habitation. In the United States, over half of the human population lives in coastal watersheds, and more than 37 million people and 19 million homes have been added to coastal areas during the last three decades (EPA 2004). Peoples' decisions to live near the water and use its resources for residential, commercial, industrial, and recreational purposes has resulted in significant modifications to shorelines (i.e., dredging, filling, armoring, clearing and grading, overwater structures, shipping and wastewater disposal). This has in turn negatively impacted the quality of nearshore habitats and the numerous estuarine-dependent species that rely on them. In Puget Sound, Washington, the nation's second largest estuary, seven salmon stocks are already extinct, and estuarine-dependent chinook (*Oncorhynchus tshawytscha*) and summer chum (*Oncorhynchus keta*) salmon have been listed as threatened under the federal Endangered Species Act (ESA). Bull trout (*Salvelinus confluentus*), which are thought to use the nearshore for feeding and migration, are also listed as threatened under the ESA. Coho salmon (*Oncorhynchus kisutch*) are being considered for ESA listing and 19 additional marine fishes, all of which are associated with nearshore habitat, were petitioned for listing because of critical population declines. Furthermore, the system's top-predator, the orca whale (*Orcinus orca*), whose prime food source includes salmon, has been petitioned for listing. While many factors have contributed to population declines, habitat loss and degradation resulting from human development has been identified as a major contributing factor.

In many U.S. estuaries, resource managers are studying various management tools to better protect these fragile and valuable ecosystems. One such tool being investigated (and in some cases used) is protective riparian "buffers" or "setbacks" along estuarine shorelines, which is similar to the more common establishment of buffers and setbacks along freshwater streams and rivers. A *buffer* is defined as a horizontal distance separating a coastal feature or resource from human activities and within which activities are typically regulated or controlled (i.e., limited) to protect the resource or minimize the risk of creating a coastal hazard. Buffer widths are typically based upon the desire to maintain a healthy "separation zone" and are determined by functions. A *setback* is defined as a distance landward of some coastal feature (e.g., the ordinary high-water mark) within which certain types of structures or activities are prohibited (National Oceanic and Atmospheric Administration [NOAA] 1998). Unlike buffers, setbacks seldom account for riparian or other coastal functions.

The use of riparian buffers and setbacks as tools to protect water quality, prevent erosion, and protect habitat structure and other functions in streams and rivers is well established; it is largely the result of an extensive body of literature documenting these functions and their associated socio-economic and biophysical benefits. Although marine riparian systems have not been subject to the same level of scientific investigation, a growing body of evidence suggests that riparian systems serve similar functions regardless of the salinity of the water bodies they border (see Desbonnet et al. 1994, Levings and Jamieson 2001). Desbonnet et al. (1994) conclude that the functional mechanisms that apply to inland riparian areas should be similarly applied to coastal areas. They point out that marine and freshwater riparian zones serve almost identical purposes, including pollutant removal, soil stability, wildlife and fish habitat, and stormwater control. Their conclusions support our hypothesis: Marine riparian systems provide functions similar to those described for freshwater riparian systems and are likely to provide additional functions unique to marine nearshore ecosystems.

The recent salmon crisis in the Pacific Northwest (PNW) is of particular interest in this study because it illustrates how narrowly we have focused our attention as resource managers. Most of what we know about salmonids comes from extensive studies of the freshwater phases of their life history. The information derived from decades of study has taught us much about the importance of water quality, sediments, flows, and the influence and importance of healthy riparian areas in freshwater systems. Yet, relatively little is known about salmon as they move from freshwater to marine conditions—for example, early life-history requirements and how these fish use the nearshore environment—even though these are critical stages in their life cycle. Similarly, we know relatively little about their life at sea. These marine phases of their life are critical to sustaining healthy salmonid populations in addition to providing critical links in our understanding of PNW ecosystems. The interdependency between upland and aquatic systems is illustrated in recent publications by Gresh et al. (2000) and Cederholm et al. (2000), who discuss the importance of marine-derived nutrients (i.e., returning salmon) in PNW forest and stream ecosystems. Their studies suggest that we not only need to preserve salmon in the system, but we need to look beyond salmon and maintain important estuarine and marine functions that will support healthy salmon populations. Without a doubt, this holds true for a multitude of other species as well.

While riparian areas and shoreline vegetation have been identified as integral and important parts of the marine nearshore ecosystem, their functions and benefits have not been adequately evaluated and integrated into shoreline management strategies. Recognizing this gap in our knowledge and the apparent links between shoreline vegetation and the nearshore ecosystem based on personal observations, we began an investigation with a preliminary review of the scientific literature and interviews with other marine scientists. Following this preliminary assessment, we conducted a more extensive literature review and assessment of riparian functions relative to marine systems. In this paper, we review riparian functions and associated benefits (i.e., ecological or social values) as they relate to the marine environment, using the most commonly reviewed freshwater riparian function topics as a template. The functions reviewed for this paper include water quality, soil stability, sediment control, wildlife habitat, microclimate, nutrient input, fish prey production, shade, and habitat structure with an emphasis on large woody debris (LWD). We also briefly review and discuss social values such as human health and safety, and aesthetics. In addition, we assess the relationship between current regulatory and management strategies and their effectiveness in protecting riparian and marine resources and the ecosystem as a whole. This paper is not intended to provide an exhaustive review of the literature, but rather a review of the scientific, planning, and resource management studies, concepts, and tools that have been used to identify and protect functions and values of riparian systems and their relationship to marine ecosystems. In addition to presenting the above-stated reviews and assessments, we provide a foundation to enhance discussions of shoreline management and improve resource protection through an increased understanding of nearshore and marine riparian ecosystems.

The terms "marine" and "estuarine" are used interchangeably in this report to cover the diverse and complex array of shorelines with saltwater influence found in Washington State. We also use the term "nearshore" to describe the area that tends to have the highest productivity, is the part of the marine ecosystem that includes and is most likely influenced by riparian interactions, and is also affected the most by anthropogenic disturbances/modifications. For this review, the nearshore is defined as the outer limit of the photic zone (approximately -20 m below MLLW) extending landward to include coastal landforms such as the backshore, sandspits, coastal bluffs, coastal wetlands, and riparian areas on or adjacent to any of these areas. In addition, the nearshore environment includes subestuaries such as the tidally influenced portions of river and stream mouths. Puget Sound is the focus of our attention in this report for a number of reasons, including the following:

1. It is the second largest estuary in the United States, exhibiting a wide range of both marine and estuarine characteristics.
2. It supports the richest and most complex fish and wildlife habitat and species diversity found in Washington State.
3. It supports the greatest urban density and growth of any region in the state.
4. It has a history of substantial habitat modification, loss, and degradation; species extinction and extirpation; and fish and wildlife population reductions.
5. Resource managers are currently charged with finding recovery solutions for several Puget Sound salmonid species listed under the Endangered Species Act.
6. A significant portion of Puget Sound's shorelines has already been modified by development and the remainder is increasingly threatened.

Marine Riparian Functions

Ecological Functions

Hydrological, geological, biological, oceanographic, and meteorological processes form and maintain marine habitat structure and functions. The interactions of these processes determine the natural physical, chemical, and biological elements of the ecosystem. Water delivered to the Puget Sound basin in the form of rain and snow percolates through the soils and off the land. The water entering Puget Sound in streams, springs, and seeps delivers sediments, nutrients, and organic matter. It may also deliver harmful levels of silt and contaminants. The rate and mechanism of delivery greatly influences the quality of the water and its influence on associated biotic communities. Therefore, the character of the land adjacent to marine shorelines and the transport mechanisms have a significant influence on the health and integrity of the nearshore ecosystem. The processes, structure, and functions of marine nearshore systems are complex and not well understood. However, with the limited information that we do have for the nearshore environment, along with an understanding of other aquatic ecosystems and the application of basic ecological principles, we are able to identify factors that result in habitat degradation and potentially limit species survival.

One element of the nearshore ecosystem that has received very little attention is the contribution of riparian functions. Our review of the literature has revealed many marine–riparian ecosystem linkages that have previously received little attention or discussion. It has also enabled us to better understand the importance of marine riparian systems and the environmental impacts associated with altered or lost riparian functions. For example, Shreffler et al. (1994) conclude that altering the physical conditions of the shoreline can cause changes in the biological structure and functioning of shoreline habitats and can also alter use of these habitats by fish, shellfish, birds, and other organisms. Furthermore, removal of shoreline vegetation reduces shade and large woody debris (LWD), which affects the supply of terrestrial insects (that salmon feed on), epibenthic prey resources, and the spawning habitat of baitfish, which are prey resources of larger juvenile and resident salmon (Simenstad 1998). Marine riparian areas provide a variety of ecological functions integral to the marine ecosystem. They also provide a number of social benefits as well. These functions and benefits include the following:

Ecological functions:

1. soil and slope stability
2. sediment control
3. wildlife habitat
4. microclimate
5. water quality
6. nutrient input
7. fish prey production
8. habitat structure (e.g., large woody debris)
9. shade

Social values:

1. human health and safety
2. aesthetics

The following sections provide a review of each of these ecological functions and social values. Cultural and commercial values (e.g., marketable fish and shellfish), among other social values, are also important, but were not reviewed for this manuscript.

Soil and Slope Stability

The effects of natural or geological (surface) erosion are everywhere to be seen, but this natural erosion works slowly.… Because it works so slowly, the effects of this type of erosion are hardly felt and present no serious problem. The real problem today is not natural erosion, but the intensification of this action, known as accelerated erosion. Unlike natural erosion, accelerated erosion is the result of human activities. (Wood 1938)

Vegetation affects both the surficial and mass stability of slopes in significant and important ways, ranging from mechanical reinforcement and restraint by the roots and stems to modification of slope hydrology as a result of soil moisture extraction via evapotranspiration. In a mature forest, approximately one-third of rainfall may be absorbed and evaporated back prior to reaching the ground. The remaining water is absorbed by forest duff and roots with a small percentage left to infiltrate into the ground. One dramatic example of this process is that a mature conifer can absorb up to 100 gallons of water per day (Dunne and Leopold 1978). The end result is that only a small fraction of the total rainfall actually infiltrates into the ground, or runs off of the land through this extensive, natural filtration system.

Considering the relatively high level of annual rainfall in the Pacific Northwest (relative to many other marine regions), water that is not intercepted by the tree canopy, understory, or shrubs will infiltrate into the ground, or run off the surface. This can lead to significant surficial erosion of soils that results in lost topsoil, siltation, burial of aquatic environs, and the introduction of contaminants into waterways. In addition, rainfall not intercepted or absorbed by vegetation also increases soil saturation, increasing the potential for landslides. Landslides appear to be much more frequent in areas where vegetation has been removed by development than in undisturbed areas of Puget Sound.

Vegetation, once established, provides a self-perpetuating and increasingly effective permanent erosion control (Kittredge 1948, Menashe 1993). Soils, slope height and angle, drainage, and other factors are also very important in determining susceptibility to erosion. However, for all shorelines, and particularly those in areas with steep and eroding bluffs, native vegetation is usually the best tool for keeping the bluff intact and for minimizing erosion (Broadhurst 1998). The loss or removal of slope vegetation can result in increased rates of erosion and higher frequencies of slope failure. This cause-and-effect relationship can be demonstrated convincingly by the many field and laboratory studies reported in the technical literature. Disturbing the face or toe of a bluff or bank may cause destabilization, slides, and cave-ins (Clark et al. 1980).

Removal of the vegetation that helps to stabilize the face, or excavation along the face, increases the chance of slumping, which results in imperiled structures, lost land, a disruption to the ecological edge-zone, and increased sedimentation to the aquatic environment (Clark et al. 1980).

Often, it is not simply the removal of native vegetation and forest duff that contributes to decreased soil stability. As shoreline properties are developed, the increase in impervious surfaces (e.g., roads, driveways, foundations, etc.) concentrates and increases runoff. This exacerbates erosional problems by increasing the volume of water and energy of flows that cut away and destabilize the land. Despite attempts to use detention, infiltration, and other forms of stormwater control, erosion and destabilization problems are often realized in other areas "downstream" or result in direct discharge to waterways, producing another set of problems (e.g., water quality, hydrology, siltation, habitat loss, and degradation). The relationship of these problems to riparian and aquatic ecosystems is clearly one of lost functions, reductions in fish and wildlife, and an increased threat to human health and safety.

Sediment Control

The control of sediments entering waterways is one of the most commonly identified functions of riparian areas in freshwater and coastal riparian studies. Most discussions of sediment control are addressed in the context of functional mechanisms of pollution abatement and soil stability provided by riparian buffers. Since most pollutants associated with stormwater are adsorbed to sediments (Karr and Schlosser 1978), trapping sediments also removes a certain percentage of the pollutant load carried in surface runoff (Desbonnet et al. 1995). Desbonnet et al. (1995) also state: "Pollutants that adsorb to sediments, and therefore can be effectively treated by riparian vegetation, include most forms of nitrogen and phosphorus, hydrocarbons, PCBs, most metals, and pesticides. Bacterial and viral pathogens are additional contaminants of concern (Thom et al. 1988, PSWQA 1995, Desbonnet et al. 1995) that may also be attenuated by riparian vegetation. While sediments are the most easily removed pollutant (Desbonnet et al. 1995), total suspended solids (TSS) and other pollutants, such as nitrogen and phosphorus, require wider buffers for filtration and uptake by vegetation. Desbonnet et al. (1994) determined that a 25-m riparian buffer would remove approximately 80% of the sediment load, whereas removing approximately 80% of nitrogen and TSS required 60 m. Removing approximately 80% of phosphorus required an 85-m buffer. But while sheet and subsurface flows through a buffer make use of the soils and vegetation, conveying stormwater through a buffer via a ditch or pipe will provide little filtration and defeat the purpose of the buffer in providing protection to the aquatic system.

In addition to the various pollutants associated with sediments, fine sediments can have a dramatic physical effect on aquatic organisms. Siltation can clog the breathing apparatus (i.e., gills) of fishes and invertebrates, inhibit proper respiratory function in eggs and larvae (suffocation), alter substrates, and bury benthic organisms. Siltation and erosion controls have long been recognized as best management practices for development projects regardless of their proximity to a water body. Yet, many control practices have proven to be inadequate, especially for projects conducted during winter in the Pacific Northwest. The most common recommendations for silt and erosion control in the technical literature are to minimize vegetation removal in the area being cleared, maintain vegetated buffers, detain runoff on site, and provide water-quality treatment.

The inherent qualities of riparian vegetation to slow runoff, stabilize soils, take up nutrients and other contaminants, and reduce siltation are common knowledge and serve even greater functions in protecting water bodies from contamination. However, the functional ability of riparian areas to handle sediment loading depends greatly upon vegetation structure (i.e., type, age, density), steepness of slope, width of buffer, and level of disturbance and volume of contaminants being introduced from above the riparian area. Maintaining riparian vegetation can be a relatively simple, long-term, and cost-effective method of pollution abatement. Re-establishing riparian vegetation may be costly, but the long-term benefits are likely to greatly outweigh such costs.

Wildlife Habitat

Healthy (i.e., intact and functional) riparian systems along marine shorelines support abundant and diverse assemblages of wildlife. Of the 331 wildlife species known to inhabit all of King County, Washington (King County 1987; Kate Stenberg, King County Department of Natural Resources, Seattle, pers. comm.) we identified 263 wildlife species (9 amphibians, 5 reptiles, 192 birds, 57 mammals) known or expected to be associated with marine riparian habitat. This represents 79.5% of all wildlife species found in King County (Table 1**)**. The Table 1 listing represents only those species suspected of having a dependence on, or association with marine riparian zones (e.g., utilization for feeding, migration, reproduction, prey/nutrient production) and does not reflect species such as marine mammals, other birds and fishes that may have less well-defined associations with marine riparian functions. This would potentially include hundreds of additional species.

Many wildlife species are dependent upon riparian areas for their entire life cycle, with requirements for feeding, breeding, refuge, cover, movement, migration, and climate that are intricately interwoven into the ecological balance of riparian structure, functions, and processes. Other wildlife may only depend on riparian areas during a specific life stage, for limited periods during seasonal migrations, or simply as a migration corridor. Regardless of the timing, the availability and condition of riparian habitat can determine their survival, and many wildlife species have been extirpated due to the dramatic alteration and loss of marine riparian habitat.

Vegetation and other characteristics of riparian areas in Puget Sound are diverse and greatly influenced by myriad physical processes such as exposure, tidal inundation, waves, hydrology, littoral drift, and erosion potential. However, excluding subestuaries (stream and river mouths), most riparian areas immediately adjacent to the waters of Puget Sound comprise mixed conifer and deciduous forests. In terms of habitat type and species com-

Table 1

AMPHIBIANS
☒ Northwestern Salamander
☒ Long-Toed Salamander
☐ Pacific Giant Salamander
☐ Van Dyke's Salamander
☒ Ensatina
☒ Western Red-Backed Salamander
☒ Rough-skinned Newt
☒ Tailed Frog
☒ Western Toad
☒ Pacific Treefrog
☒ Red-legged Frog
☐ Cascades Frog
☐ Spotted Frog
☐ Bullfrog (I)
TOTAL AMPHIBIANS: 14

REPTILES
☒ Northern Alligator Lizard
☒ Western Fence Lizard
☐ Rubber Boa
☒ Common Garter Snake
☒ Western Garter Snake
☒ Northwestern Garter Snake
☐ Painted Turtle
☐ Western Pond Turtle
☐ Snapping Turtle (I)
☐ Slider (I)
TOTAL REPTILES: 10

MAMMALS	MAMMALS (cont'd)	MAMMALS (cont'd)
☒ Virginia Opposum (I)	☒ Raccoon	☒ Beaver
☒ Cinerous Shrew	☒ Marten	☒ Deer Mouse
☒ Trowbridge Shrew	☐ Fisher	☒ Northwestern Deer Mouse
☒ Vagrant Shrew	☐ Short-tailed Weasel	☒ Bushytailed Woodrat
☒ Montane Shrew	☒ Long-tailed Weasel	☒ Black Rat(I)
☒ Water Shrew	☒ Mink	☒ Norway Rat (I)
☒ Marsh Shrew	☐ Wolverine	☒ House Mouse(1)
☒ Townsend's Mole	☒ River Otter	☒ Southern Red-backed Vole
☒ Coast Mole	☐ Spotted Skunk	☐ Heather Vole
☒ Shrew Mole	☒ Striped Skunk	☐ Long-tailed Vole
☒ Little Brown Bat	☒ Mountain Lion (Cougar)	☐ Townsend's Vole
☐ Keen's Myotis	☒ Bobcat	☐ Creeping Vole
☒ Yuma Myotis	☒ Elk	☒ Water Vole
☐ Long-eared Myotis	☒ White-Tailed Deer	☒ Muskrat
☐ Long-legged Myotis	☒ Mule Deer	☒ Pacific Jumping Mouse
☐ California Myotis	☐ Mountain Goat	☐ Porcupine
☐ Silver-haired Bat	☒ Mountain Beaver	☒ Nutria (Coypu) (I)
☒ Big Brown Bat	☒ Townsend's Chipmunk	☐ Pika
☐ Hoary Bat	☐ Yellow Pine Chipmunk	☐ Snowshoe Hare
☐ Townsend's Big-eared Bat	☐ Hoary Marmot	☒ Eastern Cottontail (I)
☒ Coyote	☐ Cascade Golden-mantled Ground Squirrel	
☐ Gray Wolf	☒ Eastern Gray Squirrel (I)	
☒ Red Fox	☒ Douglas' Squirrel	
☒ Black Bear	☒ Northern Flying Squirrel	
☐ Grizzly Bear		*TOTAL MAMMALS: 69*

Table 1. King County wildlife species list (excluding marine mammals). Species checked are those that are known or expected to have a dependence, or association with marine riparian areas (i.e., utilization for feeding, breeding, refuge, migration, prey/nutrient production, etc).
NOTE: Checklist is based upon documented occurrence and/or professional opinion of reviewers. Additional research is needed to verify ecological linkages and utilization of marine riparian areas by wildlife.

BIRDS	BIRDS (cont'd)	BIRDS (cont'd)	BIRDS (cont'd)	BIRDS (cont'd)
☒ Red-throated Loon	☒ Red-breasted Merganser	☒ Parsitic Jaeger	☒ Hammond's Flycatcher	☒ Cedar Waxwing
☒ Pacific Loon	☒ Ruddy Duck	☒ Franklin's Gull	☒ Dusky Flycatcher	☒ European Starling (I)
☒ Common Loon	☒ Osprey	☒ Bonaparte's Gull	☒ Pacific-slope Flycatcher	☒ Orange-crowned Warbler
☒ Pied Billed Grebe	☒ Bald Eagle	☒ Heermann's Gull	☐ Say's Phoebe	☐ Nashville Warbler
☒ Horned Grebe	☒ Northern Harrier	☒ Mew Gull	☐ Western Kingbird	☐ Yellow Warbler
☒ Red-necked Grebe	☒ Sharp-shinned Hawk	☒ Ring-billed Gull	☐ Eastern Kingbird	☒ Yellow-rumped Warbler
☒ Eared Grebe	☒ Cooper's Hawk	☒ California Gull	☒ Northern Shrike	☒ Black-throated Gray Warbler
☒ Clark's Grebe	☐ Northern Goshawk	☒ Herring Gull	☒ Cassin's Vireo (Solitary)	☒ Townsend's Warbler
☒ Western Grebe	☒ Red-tailed Hawk	☒ Thayer's Gull	☒ Hutton's Vireo	☐ Hermit Warbler
☒ Double-crested Cormorant	☐ Rough-legged Hawk	☒ Western Gull	☒ Warbling Vireo	☒ MacGillivray's Warbler
☒ Brandt's Cormorant	☐ Golden Eagle	☒ Glaucous-winged Gull	☐ Red-eyed Vireo	☒ Common Yellowthroat
☒ Pelagic Cormorant	☐ American Kestrel	☒ Caspian Tern	☐ Gray Jay	☒ Wilson's Warbler
☒ American Bittern	☒ Merlin	☒ Common Tern	☒ Western Scrub Jay	☒ Western Tanager
☒ Great Blue Heron	☒ Peregrine Falcon	☒ Black Tern	☒ Steller's Jay	☒ Spotted Towhee
☒ Green Heron	☒ Gyrfalcon	☒ Common Murre	☐ Blue Jay	☐ Chipping Sparrow
☒ Black-crowned Night Heron	☒ Ring-necked Pheasant (I)	☒ Pigeon Guillemot	☒ American/Northwestern Crow	☐ Vesper Sparrow
☒ Turkey Vulture	☐ Spruce Grouse	☒ Marbled Murrelet	☒ Common Raven	☒ Savannah Sparrow
☒ Tundra Swan	☐ Blue Grouse	☒ Ancient Murrelet	☐ Horned Lark	☒ Fox Sparrow
☒ Trumpeter Swan	☐ White-tailed Ptarmigan	☒ Rhinoceros Auklet	☒ Purple Martin	☒ Song Sparrow
☒ Greater White-Fronted Goose	☐ Ruffed Grouse	☒ Rock Dove (I)	☒ Tree Swallow	☒ Lincoln's Sparrow
☒ Snow Goose	☐ California Quail	☒ Band-tailed Pigeon	☒ Violet-green Swallow	☒ White-throated Sparrow
☒ Ross's Goose	☒ Virginia Rail	☒ Mourning Dove	☒ Northern Rough-winged Swallow	☒ Golden-crowned Sparrow
☒ Brant	☒ Sora	☒ Barn Owl	☐ Bank Swallow	☒ White-crowned Sparrow
☒ Canada Goose	☒ American Coot	☒ Western Screech Owl	☒ Cliff Swallow	☐ Harris's Sparrow
☒ Wood Duck	☐ Sandhill Crane	☒ Great Horned Owl	☒ Barn Swallow	☒ Snow Bunting
☒ Green-winged Teal	☒ Pacific Golden Plover	☒ Snowy Owl	☒ Black-capped Chickadee	☒ Dark-eyed Junco
☒ Mallard	☒ Black-bellied Plover	☒ Northern Pygmy Owl	☐ Mountain Chickadee	☒ Lapland Longspur
☒ Northern Pintail	☒ Semipalmated Plover	☐ Spotted Owl	☒ Chestnut-backed Chickadee	☐ Black-headed Grosbeak
☒ Blue-winged Teal	☒ Killdeer	☒ Barred Owl	☒ Bushtit	☐ Lazuli Bunting
☒ Cinnamon Teal	☒ Greater Yellowlegs	☐ Long-eared Owl	☒ Red-breasted Nuthatch	☒ Red-winged Blackbird
☒ Northern Shoveler	☒ Lesser Yellowlegs	☒ Short-eared Owl	☒ Brown Creeper	☐ Western Meadowlark
☒ Gadwall	☒ Solitary Sandpiper	☐ Northern Saw-whet Owl	☒ Bewick's Wren	☐ Yellow-headed Blackbird
☒ Eurasian Widgeon	☒ Spotted Sandpiper	☒ Common Nighthawk	☐ House Wren	☐ Brewer's Blackbird
☒ American Widgeon	☒ Whimbrel	☐ Black Swift	☒ Winter Wren	☒ Brown-headed Cowbird
☒ Canvas Back	☒ Ruddy Turnstone	☒ Vaux's Swift	☒ Marsh Wren	☒ Bullock's Oriole
☒ Red Head	☒ Surfbird	☒ Anna's Hummingbird	☐ American Dipper	☐ Gray-crowned Rosy Finch
☒ Ring-necked Duck	☒ Sanderling	☒ Rufous Hummingbird	☒ Golden-crowned Kinglet	☐ Pine Grosbeak
☒ Greater Scaup	☒ Semipalmated Sandpiper	☒ Belted Kingfisher	☒ Ruby-crowned Kinglet	☒ Purple Finch
☒ Lesser Scaup	☒ Western Sandpiper	☐ Lewis's Woodpecker	☐ Western Bluebird	☒ House Finch
☒ Harlequin Duck	☒ Least Sandpiper	☒ Red-breasted Sapsucker	☐ Mountain Bluebird	☒ Red Crossbill
☒ Black Scoter	☒ Baird's Sandpiper	☒ Downy Woodpecker	☒ Townsend's Solitaire	☐ White-winged Crossbill
☒ Surf Scoter	☒ Pectoral Sandpiper	☒ Hairy Woodpecker	☒ Swainson's Thrush	☐ Common Redpoll
☒ White-winged Scoter	☒ Dunlin	☐ Three-toed Woodpecker	☒ Hermit Thrush	☒ Pine Siskin
☒ Common Goldeneye	☒ Short-billed Dowitcher	☒ Northern Flicker	☒ American Robin	☒ American Goldfinch
☒ Barrow's Goldeneye	☒ Long-billed Dowitcher	☒ Pileated Woodpecker	☒ Varied Thrush	☒ Evening Grosbeak
☒ Bufflehead	☒ Common Snipe	☒ Olive-sided Flycatcher	☐ Northern Mockingbird	☒ House Sparrow(I)
☒ Hooded Merganser	☒ Wilson's Phalarope	☒ Western Wood-Pewee	☒ American Pipit	
☒ Common Merganser	☒ Red-necked Phalarope	☒ Willow Flycatcher	☒ Bohemian Waxwing	***TOTAL BIRDS: 238***

\\wlsnt2\wordproc\F\FORMS\Marine_Riparian_Wildlife_J_Brennan.doc position, these riparian areas are similar to those found along Puget Sound lowland streams and other riparian areas in western Washington State. Therefore, a similar value assessment of riparian wildlife habitat is warranted. Wildlife habitat requirements in riparian systems are complex and have received much review and analysis. For example, Knutson and Naef (1997), Desbonnet et al. (1994), and Wenger (1999) have performed extensive literature reviews to determine buffer widths required to maintain riparian functions for wildlife. For Washington State, Knutson and Naef (1997) determined that the average width reported to retain the riparian function for wildlife habitat was 88 m. In their literature review of wildlife habitat protection, Desbonnet et al. (1994) recommend 60-100 m for general wildlife habitat, 92 m for protecting important wildlife habitat, and 600 m for protecting critical species. Unfortunately, little discussion and even less effort has been focused on preserving marine riparian areas for wildlife species in Puget Sound or elsewhere. This has resulted in a dramatic loss and fragmentation of riparian habitat and associated wildlife. Buffer requirements for freshwater systems may be substantially less than for some marine and estuarine systems because of the influences of wind, salt spray, desiccation, and general microclimatic effects on vegetation and associated wildlife (Klaus Richter, King County, Department of Natural Resources and Parks, Seattle, pers. comm.).

One of the greatest impacts of urbanization on wildlife comes from habitat fragmentation (Stenberg et al. 1997, Knutson and Naef 1997). The isolation of remnant habitat parcels makes utilization and recolonization by wildlife difficult or impossible (Knutson and Naef 1997). This is of particular concern for species with low mobility such as amphibians (Richter 1995, Knutson and Naef 1997). Because many wildlife species depend upon wide, continuous corridors, and separation from the disturbance of urbanization, fragmented and discontinuous riparian habitat provides limited value to a wide range of species and will ultimately support greatly reduced species diversity and abundance. This is not to say that small tracts of remaining riparian habitat are of no value. Rather, it suggests that species diversity and abundance, along with other wildlife benefits and riparian functions, may be improved with efforts to reconnect and expand remaining riparian (and upland) areas.

Washington State claims to have nearly 2.5 million wildlife watchers over the age of 16, with expenditures of $980 million for wildlife watching activities in 2001 (U.S. Fish and Wildlife Service [USFWS] 2001). Much of this wildlife viewing occurs along marine shorelines, from the land and from the water. Considering the species diversity and abundance of wildlife supported by riparian areas, there appears to be both economic and biological arguments for their maintenance and protection.

Microclimate

Riparian plant and animal communities are greatly influenced by marine waters—especially those communities immediately adjacent to marine waters—temperature and moisture regulation, tidal inundation, wind exposure, and salt spray. Marine littoral communities are, in turn, influenced by riparian condition. The interaction of these two systems creates an ecotone, a unique transition zone from a marine system to an upland ecosystem that supports a diverse assemblage of plants and wildlife.

The greatest influence of marine waters on riparian communities is temperature; marine waters keep lowland areas cooler in the summer and warmer in the winter. Temperature and moisture are also regulated by the amount of vegetative cover on the land. Together, these factors contribute to microclimates upon which fish and wildlife depend, especially climate-sensitive species such as amphibians. Even the quality of the soil (biological, chemical, and physical properties) is influenced by climate, thereby affecting conditions for plants and animals.

Removing vegetation in upland and riparian areas increases exposure of the land and water to sun and decreases organic matter, resulting in elevated runoff and increased temperatures for water entering marine systems, desiccation of soils, and increased stress for animals dependent upon cool, moist conditions. Cleared areas become hotter in the summer and colder in the winter, have increased evaporation due to wind and sun exposure, have reduced humidity, and may experience increased soil instability.

Microclimates contribute to higher species diversity and abundance along marine shorelines compared with nonriparian areas. As marine shorelines have become urbanized, large volumes of riparian vegetation have been displaced by concrete, asphalt, structures, and landscaping, which changes habitat structure and results in temperature and moisture changes. Changes in microclimate and habitat structure also result in concurrent changes in species composition.

Water Quality

Degradation of urban waterways is directly linked to urbanization and has been exacerbated by the lack of adequate storage, treatment, and filtration mechanisms for runoff. The major pollutants found in runoff from urban areas include sediment, nutrients, oxygen-demanding substances (e.g., organic compounds), road salts, heavy metals, petroleum hydrocarbons, pathogenic bacteria, and viruses (U.S. Environmental Protection Agency [USEPA] 1993). Many contaminants bind to sediments, which, when suspended, constitute the largest mass of pollutant loadings to receiving waters from urban areas (USEPA 1993). Clearing, grading, and other construction practices are the major source of sediment erosion. In addition to the damages caused by chemical constituents, excessive sedimentation results in burial and siltation, which can have severe, adverse effects on aquatic biota.

Typically, clearing and grading is followed by the installation of impervious surfaces such as roads, buildings, sidewalks, and parking lots. Furthermore, landscaping practices and the compaction of soils that occurs with development results in vast areas of relatively impermeable soil. Rainfall and other runoff is not retained and gathers in volume, velocity, and contaminants as it flows over the now-converted landscape toward its ultimate destination—a waterway such as Puget Sound. Water collected in stormwater systems, sewage, and discharges from industrial sources may or may not be treated and contains varying levels of silt, waste, and chemical constituents that could otherwise be absorbed or removed by allowing for infiltration, detention, and absorption by soils and vegetation.

Pesticide, herbicide, and fertilizer application can have dramatic impacts on fish and wildlife through direct and indirect contact. Improper application, excessive concentrations, and overuse of pesticides and fertilizers are common practices in urban shoreline areas where artificial landscapes are desired by landowners. Harmful chemical constituents are transported to marine and estuarine waters through a number of transport mechanisms (i.e., sediments, surface runoff, springs, seeps, streams) and are taken up by aquatic organisms in the water through prey organisms and other food sources. Contaminants also accumulate in sediments that can affect benthic and epibenthic organisms through physical contact. Direct effects include mortality to adults, juveniles, or embryos; reduced reproductive success; birth defects; anorexia and loss of body-weight; retarded growth; and changes in species composition. Indirectly, treatments with pesticides (particularly insecticides and herbicides) can reduce plant and insect food sources for wildlife species (Knutson and Naef 1997) and fishes. Reduced and contaminated food sources can cause stress, reduced growth and survival, relocation, and higher susceptibility to predation.

Fertilizers and other urban and agricultural runoff contribute to additional indirect impacts by introducing high levels of organic nutrients, petroleum byproducts, and other contaminants into the aquatic system. The increase in nutrients can cause plankton blooms, which may consume oxygen as the plankton die. This process is known as eutrophication. Eutrophication in the nearshore has been identified as a concern by resource managers and scientists (Broadhurst 1998). It is often the result of poorly functioning septic systems and other unfiltered runoff. Eutrophication is particularly acute in water bodies with poor tidal flushing or extended residence times like Hood Canal, Whidbey basin and South Puget Sound. It can also occur in embayments, particularly in heavily urbanized areas.

Contamination has also had a direct economic effect on the region's shellfish industry. Washington is the second largest producer of oysters and clams in the nation and the leading producer of farmed oysters and clams. Clean water is critical for the industry and the public who enjoy harvesting shellfish (Washington Department of Health/Puget Sound Action Team [WDOH/PSAT] press release, June 2003). In 1992, 32% of classified commercial shellfish-growing areas in Puget Sound and Juan de Fuca Strait were either restricted or prohibited for harvesting owing to water-quality issues (Levings and Thom 1994). In 2003, the WDOH identified 20 threatened shellfish areas in a record number of counties (12) according to their Early Warning System (WDOH/PSAT 2003). In most urban and urbanizing areas of Puget Sound, sport harvest of clams is restricted because of contaminants derived from urban runoff, failing septic systems, and other nonpoint pollution sources. Despite efforts to upgrade and expand wastewater treatment facilities, increasing urbanization and destruction of riparian zones will continue to contribute to degraded water quality and will likely result in increased harvest restrictions.

The effects of these contaminants become most apparent through analysis of higher-order predators such as marine mammals. In his review of contaminants found in Puget Sound marine mammals, Calambokidis (1995) found that concentrations of PCBs in harbor seals (*Phoca vitulina*) in the 1970s were among the highest reported worldwide. He also reported that these contaminants have been linked to a variety of disorders in marine mammals, including premature births, reproductive failure, and immunosuppression. More recently, high levels of PCBs have been found in orca whale tissues, which is suspected as a possible cause of population decline. This concern has led to the listing of orcas as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and a petition for listing orcas under the Endangered Species Act in the United States.

According to state water-quality assessments, the leading nonpoint pollution contributors to estuarine waters are urban runoff (including construction and development activities and onsite disposal systems) and agriculture (USEPA 1993). Other significant nonpoint contributors in some coastal watersheds include silviculture, marinas, and hydromodification. Furthermore, the loss and degradation of wetlands and riparian areas has adversely impacted coastal water quality (USEPA 1993).

The use of riparian areas for pollution abatement is well documented (e.g., Phillips 1989, Groffman et al. 1990, Desbonnet et al. 1994, Knutson and Naef 1997, Lorance et al. 1997a,b, Rein 1999, Wenger 1999). In addition, vegetated buffers are known to be efficient and cost effective. Our review of the literature regarding the use of riparian buffers for pollution control in estuaries indicates that the level of effectiveness depends upon a number of factors including the following:

- soils
- geomorphology
- hydrology
- biological processes (e.g., microbial activity)
- vegetation type
- steepness of slopes
- annual rainfall
- level of pollution
- type of pollutants
- surrounding land uses
- buffer width

In an analysis of multiple soil types found in several states along the Atlantic coast, Phillips (1989) found that a 91-m vegetated buffer area would provide sufficient filtration for nonpoint pollution concerns around estuaries. Clark et al. (1980) recommended 24-m minimum buffers for slopes of 20% with slight erosion, and 46-m minimum buffers for 30% slopes with severe erosion for controlling agricultural runoff. Lee and Olsen (1985) found that the majority of nitrogen loading in estuarine lagoons (70-90%) and resultant algal blooms and eutrophication resulted from upland residential development and application of herbicides and pesticides. In addition, a number of studies link declines in seagrasses (i.e., *Zostera* spp.) and changes in species composition to degraded water quality associated with shoreline development (Short and Burdick 1996, Pennings et al. 2002). Resolving these problems entailed recommendations that included maintaining and replacing septic systems, reducing further development, and a requirement for natural vegetation buffers. Rein (1999) not only recommended vegetated buffer strips to reduce siltation and pollutants from agriculture, but quantified the economic benefits to the grower and society that result from using vegetation for erosion control and filtration of contaminants. Similarly, in a study of the cost of nutrient control in Chesapeake Bay, Butt and Brown (2000) conclude that the past decade of nutrient control experience has proven that pollution prevention would have been a much cheaper alternative in the long run. Knowing that vegetative buffers can provide significant reductions in pollutants, it can be inferred that requiring such buffers would be of great benefit and reduce costly reactionary measures to clean up waterways. However, determining appropriate buffer widths to provide pollution abatement functions will require some basic knowledge of environmental conditions (i.e., factors listed above).

Nutrient Input

One of the characteristics that makes estuaries so productive is that they act as sinks for nutrients derived from upland and marine sources. Estuarine ecosystems have a functional dependency on capturing and processing organic matter to support detritus-based food webs. Furthermore, this function depends upon the right kinds and appropriate levels of organic nutrient input.

The primary source of nutrients in the system is derived from primary producers (i.e., aquatic and terrestrial vegetation, phytoplankton). Alterations of intertidal and subtidal areas by dredging, filling, diking, overwater structures, and shoreline armoring have dramatically affected marine wetland and other aquatic vegetation (i.e., eelgrass, algae). Similarly, upland development has greatly reduced the amount of vegetation and nutrients available to the marine system.

Organic detritus is the principal energy source for food webs in estuarine and shallow, marine benthic portions of the ecosystem; the principle source of this detrital carbon is debris from macrophytes in the system (Gonor et al. 1988). For large woody debris, isopods (*Limnoria*), mollusks (*Bankia*, *Teredo*), fungi, and bacteria play important roles as agents of wood conversion and dispersion in the carbon and energy cycles of estuaries. For example, the wood-boring isopods, *Limnoria* (gribbles), transfer fine wood particles to the carbon pool of the benthic sediment system by enormously increasing the surface area of wood and effectively converting trees directly into nonbuoyant wood powder. The breakdown of this material and its contribution to carbon cycling in detrital systems is not well understood, but it may provide an important source of carbon where LWD (and other upland vegetative material) is available. Thus, reductions of LWD in the nearshore likely result in reduced detrital carbon.

Beach wrack (organic/plant material deposited on beaches that is derived from marine and upland sources) provides habitat for several taxa that, in turn, process the material for introduction into the detritus-based food web and serve as prey for higher trophic levels (i.e., fish and wildlife). Beach wrack is also processed by the mechanical action of waves and the grinding action of the sand and gravel on the beach. The structural benefits of wrack include cover and refuge from desiccation and predators. While beach wrack tends to attract both terrestrial insects and marine invertebrates, it appears that the most abundant taxonomic group is crustaceans. For example, in a survey of beach wrack infauna at North Beach, near the West Point Wastewater facility in Seattle, Washington, the numbers of crustaceans found in some beach wrack samples exceeded 10,000 per square meter (Shimek 1993). While some shorebirds are known feed on these crustaceans, little is known about links to higher trophic levels.

While food webs and trophic interactions in the nearshore are generally understood, there remain significant data gaps in our understanding of specific linkages and pathways between inputs and trophic levels. Most studies of trophic interactions are species-specific, linked to specific projects in space and time, or lack the design and goals for a larger-scale understanding of the ecosystem. Studies are typically performed by different agencies, for different purposes, and often, using different methodologies. Also, the designs of independent studies often do not lend themselves to comparing and interpreting data. For example, it is well known that fishes in the marine environment prey on a suite of organisms from various trophic levels supported by detritus. Although the importance of detritus in maintaining a prey base is well accepted, the contribution of riparian vegetation to the detritus base of the marine food web has received little attention.

In their assessment of shoreline armoring effects on selected biological resources in Puget Sound, Shreffler et al. (1994) note that increased beach erosion caused by shoreline armoring can convert the beach from a system that shows net accumulation of organic matter to one that shows net loss of organic matter on an annual or seasonal basis. Organic matter is essentially stripped from the beach or no longer accumulates as a result of the increased energy, resulting in lowering of the beach profile and loss of intertidal area due to the placement of armoring. The assessment by Shreffler et al. (1994) also illustrates that armoring results in a direct loss of riparian vegetation, alterations of sediment input, deposition and retention, nutrient flux, species assemblage shifts and ultimately, negative effects on aquatic organisms such as forage fishes, salmonids, clams, crabs, and other invertebrates. The losses due to shoreline armoring have been identified in numerous studies and reports (see Kozloff, 1974, Macdonald et al. 1994, and Broadhurst 1998 for summaries and references). Yet, little attention and fewer studies have been focused on quantifying the cumulative impacts of such losses. However, a recent study by Sobocinski (2003) clearly identifies and quantifies biological impacts associated with armored shorelines. Natural beach sites had larger amounts of beach wrack (organic debris) and significantly higher species diversity and abundance of insects and invertebrates when compared with armored/altered sites, which illustrated that shoreline armoring decreases abundance and taxa richness in both benthic and infaunal invertebrate and insect assemblages.

Fish Prey Production

Numerous studies have identified functional linkages between riparian areas and marine aquatic systems. However, few have established direct linkages between specific prey resources derived from riparian vegetation and marine fishes. Of the dietary studies of marine fishes that were reviewed for this study, it appears that salmon benefit most from riparian vegetation. The direct input of insect prey (fallout) from riparian vegetation for salmonids in freshwater systems has been well documented. However, the importance of insect fallout from riparian vegetation in juvenile salmon (and juvenile and adult cutthroat trout, *Salmo clarki*) diets in the marine environment is just being realized, and this resource may play an important role in early marine survival.

The success of salmon feeding in shallow estuarine and marine areas may have an important influence on the early marine growth and survival of the fish utilizing these areas for rearing (Pearse et al. 1982). Successful feeding and growth depends upon the availability of preferred prey in the right space and time. In the nearshore environment, sporadic dietary studies of juvenile salmonids have shown interspecific differences in prey selectivity, and intraspecific differences in space and time. However, for those species of salmonids (i.e., cutthroat trout, chinook and chum salmon) known to be most dependent upon shallow, nearshore waters, insects derived from the terrestrial environment appear to play an important role in their diets.

Several studies have shown that chum salmon prey on terrestrially derived insects in Pacific Northwest estuaries. Simenstad (1998) found that summer chum collected in Hood Canal preyed upon insects. In the central Puget Sound Basin, Cordell et al. (1998; 1999a, b) found that insects were a dominant prey item in chum stomachs and consisted of chironomid fly larvae, pupae/emergent adults, dipteran flies, and spiders. The predominance of insects, especially chironomids, found in these studies is similar to results of chum salmon diets from other estuarine sites (Congleton 1978, Northcote et al. 1979, Shreffler et al. 1992, Cordell et al. 1997, Fresh et al. 1979).

Juvenile chinook salmon have also been shown to prey upon insects in the Puget Sound nearshore and other estuaries in Washington State. Insects were identified as a significant dietary component of juvenile chinook collected off Bainbridge and Anderson islands by Fresh et al. (1981). Miller and Simenstad (1997) found that insects (chironomids and aphids) were the most important prey items for juvenile chinook at created and natural channels in the Chehalis River estuary. Studies by Cordell et al. (1997; 1998; 1999a,b) have shown similar results in juvenile chinook salmon diet studies but have also shown prey species variability among years and seasons studied in the Duwamish and Snohomish river estuaries. The importance of insects in juvenile chinook diets is also supported by studies in the Frasier River estuary (Levings et al. 1991, Levings et al. 1995), the Nisqually estuary (Pearce et al. 1982), the Puyallup River estuary (Shreffler et al. 1992), the Nanaimo estuary (Healey 1980), the Nisqually Reach area of Puget Sound (Fresh et al. 1979), and central Puget Sound (Sobocinski 2003). More recently, juvenile chinook salmon stomach contents analyzed from beach seine samples collected throughout King County shorelines in central Puget Sound show a predominance of terrestrial insects in their diet (Brennan et al 2004) (**Figure 1**). This suggests that riparian vegetation on open marine shorelines may play an important role in producing prey for juvenile salmon.

The results of these studies provide direct evidence of the importance of salt marsh and upland riparian vegetation as vital ecosystem components for providing detritus and habitat for salmonid food organisms. For example, Levings et al. (1980) found that of the 10 prey species used by chinook, chironomid larvae, pupae, and adults were most abundant in the vegetated zones, and therefore, their density might be used as an index of fish food abundance directly related to vegetation presence or coverage. Other invertebrates, such as mysids and amphipods, are connected to vegetation via detritus-based food webs as shown on the Fraser

Figure 1. Stomach contents of a 143 mm juvenile chinook salmon captured off of Maury Island (Puget Sound shoreline) on September 14, 2001. Note that contents are comprised entirely of terrestrial insects. Although juvenile salmonids feed on both marine and terrestrial organisms, this illustrates that they do have some dependency on prey derived from the adjacent uplands.

estuary (Healey 1982) and in studies of other areas (e.g., Simenstad and Wissmar 1985, Levings et al. 1991). A current food-web analysis by the University of Washington (Cordell et al., School of Aquatic & Fishery Sciences, Seattle, unpubl. data) has identified important habitats and food-web connections for chinook salmon in Puget Sound, including:

- Intertidal and shallow subtidal areas that produce amphipods and other epibenthic crustaceans. As has been established for juvenile chum salmon, these probably include intertidal flats as well as vegetation and areas of high detritus buildup.
- Nearshore vegetated terrestrial habitats that are the source of terrestrial insects in the diets.
- Feeding on planktonic grazers such as euphausiids, shrimp, and crab larvae, planktonic amphipods, and copepods.
- Feeding on other secondary pelagic consumers such as herring and other fish.

Because of limited sampling and dietary analysis of juvenile salmonids and other fishes in the nearshore environment, we need additional studies to understand the contribution of riparian vegetation to nearshore food webs and the impacts of vegetation loss along marine shorelines. However, as vegetation is eliminated, the food supply, and thus the carrying capacity of the coastal ecosystem, is likely to be reduced (cf. Levings and Jamieson 2001 for review of riparian vegetation/food web linkages).

Habitat Structure/Large Woody Debris (LWD)

Riparian vegetation and large woody debris (LWD) provide a multitude of functions in aquatic ecosystems and riparian forests. One primary role of vegetation and LWD is as habitat structure. The role and importance of LWD in freshwater lotic systems has been well documented and has led to increasing efforts to use LWD for bank stabilization and habitat restoration (e.g., Cramer et al. 2003, Johnson and Stypula 1993). Course woody debris is also an important part of estuarine and oceanic habitats, from upper tidewater of coastal rivers to the open ocean surface and the deep sea floor (Gonor et al. 1988). Yet, long before we understood or were concerned about freshwater or marine riparian systems, vast amounts of trees were cut along rivers and Puget Sound shorelines for timber and land development. Shoreline riparian forests likely were some of the earliest wood harvested owing to the ease of access and transport (logs could be floated down rivers, or rafted up the estuary for delivery to a mill site). This assumption is at least partially supported by Sedell and Duval (1985). Maser and Sedell (1994) provide a historical review of reported wood accumulations on estuarine and coastal beaches, and a number of past activities (and continuing operations) that help to understand the fate of LWD, including the following:

- West coast survey reports in the 1850s recorded that many of the drift trees in the lower Columbia River were as large a 150 feet long by 13 to 18 feet in circumference; the largest was 267 feet long (Secretary of the Treasury 1859).
- Swan (1857) reported drift trees as large as 250 feet long by 8 feet at the base, with a root span of some 20 feet, on the beach near the mouth of the Quillayute River in the Washington territory.
- The lower river and estuary banks (riparian corridor) probably were the most common sources of the largest driftwood in the bays. In the 1860s, the banks of the upper half of the Coquille estuary were lined with mature hardwoods that made travel on the Coquille like walking "dim aisles in ancient cathedrals" (Dodge 1898).
- The U.S. Army Corps of Engineers (USACE) reported that Pacific Northwest estuarine shorelines and river-mouth beaches had often been covered with driftwood in the 1870s.
- The USACE's responsibility to improve and maintain navigability led to removing significant amounts of driftwood (snags) and cutting trees along riparian corridors: "In the Tillamook River system in 1904, the U.S. Army Corps of Engineers cut down all overhanging trees along the banks of the estuary in an attempt to alleviate the woody debris problem" (Report of the Secretary of War 1904-5).
- Fishermen were also troubled by the snags and formed cooperatives to clear the rivers and estuaries of snags.
- Many sources of large wood for estuaries and beaches along the Pacific Northwest coast were exhausted by 1920.

Although similar historical data for Puget Sound were not available, the fate of LWD likely is similar to that found elsewhere in the Pacific Northwest. For example, in Puget Sound, the USACE continues to remove drift logs to reduce navigation hazards, and others snag logs for firewood, furniture, artwork and other uses.

The ecological functions of riparian vegetation and LWD in the estuarine environment are much the same as those in freshwater systems, but many of the wildlife species, and most of the fish species that have direct and indirect dependency upon riparian functions are different. Structurally, LWD provides potential 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 and algae in the marine/estuarine environment. As the source of this material has diminished, so have the many functions provided to fish and wildlife.

Bald eagles, kingfishers, and other birds use logs on beaches, tideflats, and estuarine channels as perches, which provide visibility for foraging, resting areas, and to reduce flight times (energy conservation) between foraging areas and nesting sites. Herons and egrets will use drifted trees that are partially out of the water, as well as floating logs and log rafts, for foraging and resting. Cormorants, pelicans, small shorebirds, and some waterfowl also require perches and platforms for rest between periods of foraging to spread their wings to dry their feathers and for preening themselves. Purple martins and other cavity-nesting birds will use rotting snags on beaches for nesting. This has become more common because rotting trees on land near the water have become scarce (Gonor et al. 1988). Richter (King County, DNRP, unpubl. data) has found that gulls (western, glaucous-winged, and hybrids) along the Pacific coast prefer log beaches and estuarine meadows to logless beaches and other areas for breeding. Nests are built adjacent to logs that perform many functions, including visual isolation from adjacent nesters, thermoregulatory benefits for egg development (prevents addling), and cover for newly hatched chicks. Logs enable gulls to spend less time protecting the nest and more time foraging. Hence, fewer eggs and chicks die and the remaining ones grow larger in less time. LWD is suspected to serve similar functions for other ground nesting wildlife.

The importance of LWD to aquatic organisms varies and depends highly upon LWD location. Logs high in the intertidal may become embedded and alter deposition patterns of organic litter—or beach wrack (vegetation derived from both aquatic and upland sources)—and sediments that support diverse assemblages of terrestrial and aquatic invertebrates. Although the species assemblages that use woody debris and other beach wrack are not well described, personal observations have found diverse taxonomic groups, including flying insects, spiders, mites, worms, beetles, isopods, amphipods, and many other unidentified insects and larvae. The role of beach wrack has not been well studied in the PNW. However, similar to the importance of gribbles, many of these insects may play an important role in the breakdown of organic material and contribute to carbon cycling in the nearshore ecosystem. They may also play an important role as prey for higher trophic levels in the nearshore food web, such as shorebirds and fishes.

Logs may also become waterlogged and provide substrate in intertidal zones. In estuaries where the intertidal areas comprise predominantly shifting sands and gravels, or silty substrates, solid surfaces are limited. As logs become immobilized, numerous organisms will colonize this habitat for feeding, refuge, and reproduction. Mobile invertebrates supported by this habitat (i.e., crabs, snails, limpets, nudibranchs) will find feeding opportunities, refuge, and spawning substrate. Sessile species (i.e., mussels, oysters, barnacles, and tube worms) use the space for attachment, as will algal species (e.g., *Fucus* spp.). As the logs become colonized, the surface area and habitat complexity increases. Other species will move into the area in search of prey that have colonized, or are associated with, the log while others, such as herring and other fishes, may use the attached algae or protected crevices as spawning substrate.

Vegetation and woody debris also provide refuge for fishes. While most studies have described the importance of vegetation in estuarine marshes, similar functions likely would be afforded by overhanging shoreline vegetation and woody debris on the beaches around Puget Sound. Gregory and Levings (1996) showed that, under laboratory conditions, predation by cutthroat trout on juvenile salmonids was significantly reduced in the presence of vegetation (Aitkin 1998). Considering that juvenile salmonid predators come from aquatic and terrestrial environments, the added habitat complexity and cover provided by vegetation may be a critical element of survival.

Trapping and stabilizing sediments in salt marshes and on beaches is another important structural function of vegetation and LWD in the marine environment. Gonor et al. (1988) defines salt marshes as densely vegetated, low coastal wetlands at elevations within the annual vertical range of regular tidal fluctuations that contain plants capable of growing in saturated estuarine sediments and withstanding stresses from salinity and tidal inundation. Salt marshes are important parts of estuarine systems in the PNW because of their high annual plant production rates. These marshes provide numerous functions including the following: (1) They export a significant fraction of their plant matter to the rest of the estuarine ecosystem as detritus; (2) they function as hydraulic buffers to flood and storm surges because of their extensive area; and (3) they provide important habitat to migratory waterfowl and juvenile fishes, especially salmonids, who use tidal channels (Gonor et al. 1988). Logs play important roles in forming and maintaining tidal channels by trapping sediments, which in turn become colonized by salt-marsh vegetation, further stabilizing sediments and creating complex habitat and flow patterns.

Similarly, LWD dropped onto beaches from adjacent riparian areas, or deposited during high tides, influences sediment transport and deposition. Some logs are transient while others may become embedded and serve as effective traps for sand and gravel. As sediments accumulate, back beaches, berms, and spits may be created, which are typically colonized by dune grass, beach rocket, and other plants tolerant of the conditions found in this zone (i.e., halophytes). The logs retain moisture that becomes available to dune plants and play an important role in these plants' establishment and survival. The plant stems, leaves, and complex root structure provide additional stability to the sediments. The evolution of these beach types generates new habitat for wildlife, contributes moisture and nutrients for the establishment of vegetation, adds detrital carbon to the marine system, and can greatly reduce the rate of wave-induced shoreline erosion.

Shade

For freshwater systems, shade plays an important role in regulating water temperature, which influences the survival of aquatic organisms (Beschta et al. 1987). Unlike the influence on small streams and rivers, a shaded fringe along coastal or estuarine waters is not likely to have much influence on marine water temperatures. However, solar radiation (which leads to increased temperatures and desiccation) has long been recognized as one of the classic limiting factors for upper intertidal organisms and plays an important role in determining distribution, abundance, and species composition (e.g., Ricketts and Calvin 1968, Connell 1972,). Foster et al. (1986), in their literature review of causes of spatial and temporal patterns in intertidal communities, found that the most commonly reported factor responsible for setting the upper limits of intertidal animals is desiccation. Along Puget Sound shorelines, distinct differences have been noted for substrate moisture and air and substrate temperature between shaded and unshaded beaches (personal observations). Although the influence and importance of shade derived from shoreline vegetation in the Puget Sound nearshore ecosystem is not well understood, it is recognized as a limiting factor to be considered and has prompted investigations to determine direct linkages between riparian vegetation and marine organisms.

One such link is the relationship between shade and surf smelt (*Hypomesus pretiosus*), a common nearshore forage fish found throughout the Puget Sound basin. According to Penttila (2001), surf smelt (and sand lance, *Ammodytes hexapterus*) are unique among local marine fishes in their requirement for mixed sand and gravel beaches in the upper intertidal zone as "critical habitat" for depositing and incubating eggs. Both species are considered to be important trophic links in the nearshore food web. Surf smelt also supports a fishery for human consumption. On the basis of a comparison of adjacent, shaded and unshaded spawning sites sampled in northern Puget Sound, Penttila (2001) found significantly higher egg mortality on the unshaded (sun-exposed) beaches. The study also suggests that reduced substrate moisture (increasing the potential for desiccation) in addition to direct solar radiation (direct sun exposure and elevated temperatures) may have an important influence on egg viability. However, in addition to other factors such as groundwater seeps, shading would contribute to reduction in direct exposure, temperature moderation, and higher substrate moisture. Considering the influences of temperature, moisture, and exposure on the diversity, distribution, and abundance of organisms that use upper intertidal zones, additional benefits of natural shading likely will be discovered as we investigate further.

Social Values

Human Health and Safety

Human health and safety are rarely identified in the scientific literature as one of the primary functions of riparian areas. However, at least three riparian functions—water quality, soil stability, and the ability to act as a separation zone (i.e., absorb the impacts of storm surges and other natural, physical assaults on shorelines)—apparently serve direct benefits to humans, especially in areas like the Puget Sound region. In urban areas, most people get their drinking water from a municipal water supply that comes from surface waters stored in reservoirs. These water supplies would be of much lower quality if it were not for the cleansing action of riparian forests and restrictions on forestry and development practices adjacent to these water supplies. In rural areas, many people depend upon surface and groundwater, the quality of which depends upon adequate recharge and the cleansing action of the forest and soils that act as filters. In both cases, vegetation provides stability to soils, further reducing the potential for landslides and siltation (contamination of a water supply). However, as vegetation is cleared for development and impervious surfaces displace vegetation, negative results are realized including the following:

1. The loss of filtration for surface water flowing into drinking and recreation water supplies
2. Reduced filtration for groundwater supplies
3. Reduced water volume for recharging groundwater supplies
4. Increased collection and concentration of runoff (with associated siltation and contaminants feeding into receiving waters)
5. Contamination of fish (finfishes and shellfish), game, and algal species harvested for human consumption
6. Destabilization of soils, leading to increased slide activity and threats to property and life
7. The loss of a protective "separation zone"

In addition to heavy metals, petroleum, and other chemical constituents, pathogenic bacteria and viruses pose a serious health risk to humans. Most shoreline residential properties around Puget Sound were developed using on-site septic systems. Frequently, these systems were placed between the residential structure and the water, with minimal setbacks and allowance for adequate infiltration. The drainage from these systems often infiltrates to a shallow, impermeable layer, then out through the bank and into Puget Sound. This, in conjunction with stormwater outfalls, surficial runoff, and industrial and municipal discharges, reduces water quality that has a direct link to potential human health risks. Thom et al. (1988) and others have documented eutrophication problems in Puget Sound and have expressed a concern about the likely effects on human health and biological resources. In addition, they expressed concern about predicted increases in nutrient input (thereby increasing eutrophication) as a result of increasing population.

The addition of water from a septic system, rainfall, and other runoff contributes to the likelihood of destabilized soils where the benefits of vegetation have been reduced or eliminated. Surface erosion, shallow soil creep, and deeper sliding activity is exacerbated by changes in hydrology that result from shoreline development. Shoreline erosion and sliding is a natural phenomenon on Puget Sound shorelines, where approximately half of the shorelines are classified as geologically hazardous. The overall rates of shoreline retreat are usually minor, maybe an inch or two a year, but in some areas may average as much as a half a foot per year (Macdonald et al. 1994). However, changes in hydrology, vegetation removal, and increasing impervious surfaces have had a dramatic influence on slope stability and rates of erosion.

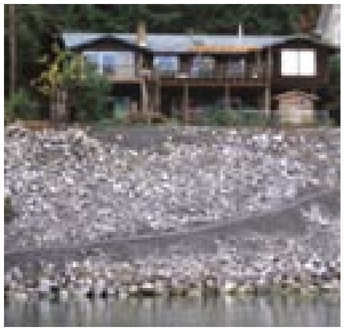
Shoreline erosion has become a critical issue to shoreline property owners, resource managers, and policy makers. The literature is replete with discussions of causes and recommendations for avoiding and controlling bluff or bank erosion. While much of the literature focuses on engineering designs for controlling erosion, the most common recommendations are simply to avoid development in geologically hazardous areas, establish development setbacks, and maintain vegetation that helps to stabilize the bank or bluff via moisture extraction, interception, and root structure. In our review of the literature of coastal slides and erosion, the earliest reference we could find in addressing erosion concerns was found in a publication prepared by The Conservation Foundation (Clark et al. 1980):

Coastal slides and erosion have long been recognized as problems in siting buildings. For example, in the 1790's George Washington reportedly studied the erosion of the Long Island coast. He ordered that the Montauk Point lighthouse at the eastern tip be built at least 200 feet back from the edge of the cliff so the lighthouse would last 200 years. At the present rate of erosion, it will last just about that long.

Many coastal structures in Washington state are often built dangerously close to the shoreline, where natural erosion can threaten property (Canning and Shipman 1994). This fact has been demonstrated many times in recent years around Puget Sound where development on or near steep shoreline slopes has caused losses of structures, property damage, high repair and replacement costs, and loss of human lives (Figure 2a,b,c). Many, if not most, of these disasters could have been avoided if we used the wisdom and will of George Washington. Prohibiting buildings in slide-prone areas, establishing proper buffers and setbacks, controlling drainage, and maintaining native vegetation would greatly reduce hazards to humans and maintain ecosystem integrity.

In addition to avoiding erosional areas and maintaining vegetation, prior recommendations (e.g., Terich 1987, Lynn 1998, Williams et al. 2001) for Puget Sound shorelines have included avoiding placing bulkheads on the beach at the expense of wetlands or productive shallow-water habitat and relocating endangered structures rather than cutting off the supply of sand to the beach. The construction of bulkheads is a common response to real or perceived erosion problems. Yet, bulkheads are not a panacea. Their installation often exacerbates bluff erosion and does not address a number of concerns, including (1) individual and cumulative environmental impacts, (2) limitations in stabilizing slopes and providing protection from wave-induced erosion, (3) loss of sediments that feed beaches, (4) loss of riparian vegetation and associated functions, (5) beach erosion and associated loss of habitat caused by bulkhead installation, and (6) other factors such as geology, hydrology, and drainage that may be the primary cause of erosion. Additional review of shoreline erosion discussion and recommendations may be found in the Coastal Erosion Management Studies prepared for the Washington Department of Ecology (WDOE 1994), Terich (1987), Manashe (1993), Myers et al. (1995), Broadhurst (1998), and Williams et al. (2001).

a. Perkins Lane, Seattle, WA.



b. Manzanita Bay, Bainbridge Island, WA.

c. Rolling Bay, Bainbridge Island, WA

Figure 2. Examples of modified (developed) steep shoreline areas, which have resulted in losses of structures (a;c), high costs of repair and environmental damage (b), and loss of human lives (c). [Photos courtesy of Washington Department of Ecology (www.ecy.wa.gov/programs/sea/landslides/)]

In summary, it appears that human health and safety would benefit greatly by maintaining appropriate setbacks from shorelines, reducing impervious areas, controlling drainage, and maintaining well-vegetated marine riparian zones.

Aesthetics

Aesthetics is not commonly recognized as a function of riparian areas, but rather as a societal value and appreciation for the visual pleasures derived from viewing natural shoreline features. Although aesthetics is not a physical or biological function of riparian areas, they do provide a function to mankind. Aesthetic qualities of riparian areas are difficult to quantify, but when preserved or restored, they enhance livability and add to the quality of life for residents and visitors (Knutson and Naef 1997). A discussion of aesthetics is difficult because it involves how people perceive their environment and where their values are rooted. One of the reasons people and businesses are attracted to the Puget Sound region is because of the aesthetic qualities and access to shorelines. Most environmental policies and regulations are founded on societal values and seek to preserve and protect them for future generations (e.g., Shoreline Management Act, RCW 75.20). Many Pacific Northwesterners view themselves as having an appreciation for their natural environment. Puget Sound is considered by some as "the boating capitol of the world," with watercraft ranging from kayaks to large sailboats and motor vessels being used to enjoy the area's aquatic resources and natural shoreline beauty. Living on and having access to shorelines is also highly valued. Businesses often choose to locate in the Puget Sound region based on "livability" criteria. Fishing, wildlife viewing, hiking, cycling, and other outdoor activities are very popular, support the regional economy, and are the very reasons people get outside to enjoy the water, trees, wildlife, and incredible views available to us.

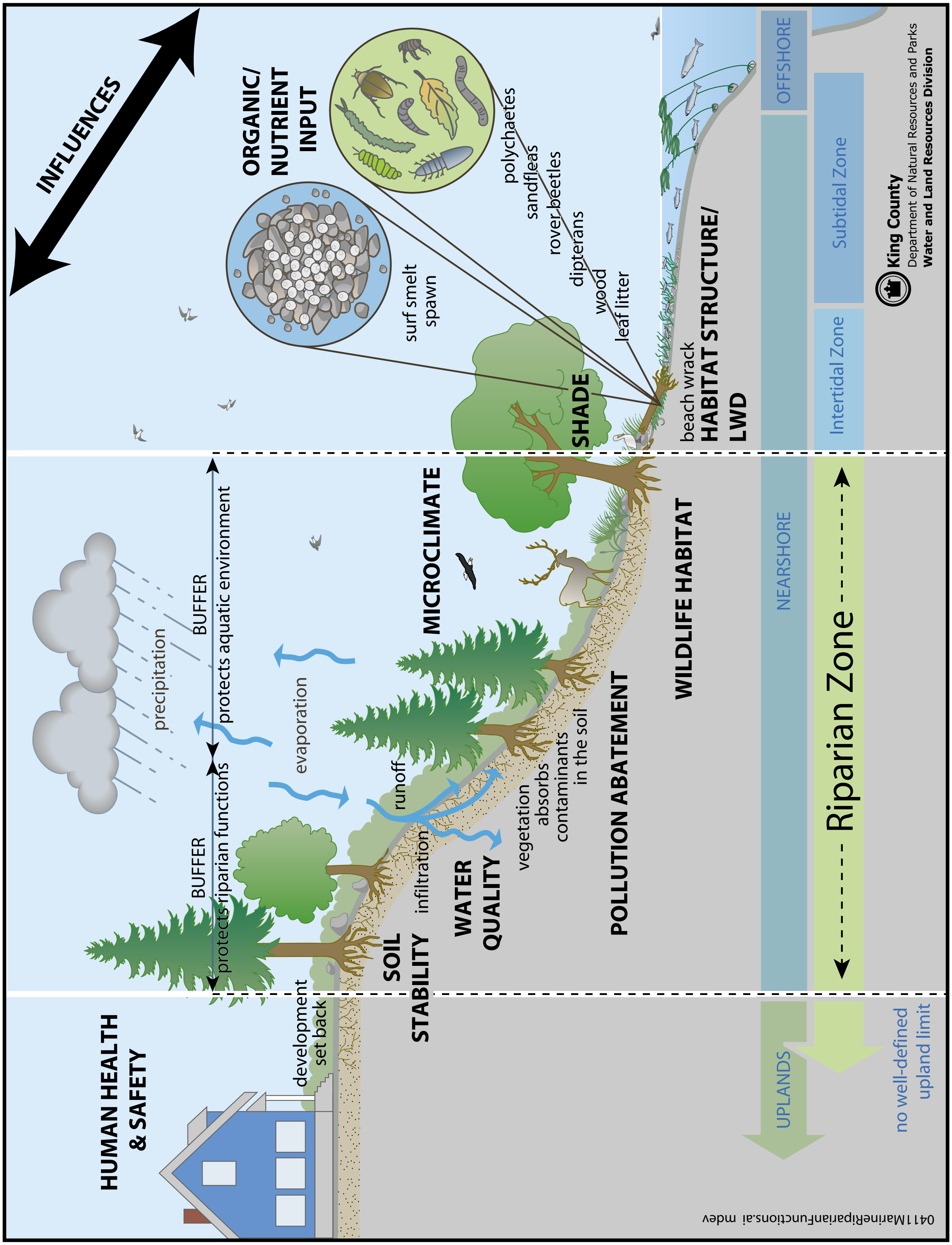
A Conceptual Model

Future progress in riparian management and marine ecosystem conservation not only requires additional empirical data, but a conceptual foundation for establishing linkages and stating assumptions. On the basis of our literature review and understanding of the Puget Sound nearshore ecosystem, there appears to be sufficient evidence of direct and indirect riparian–aquatic linkages that enable us to display known or assumed functions in a conceptual model (**Figure 3**). This conceptual model provides a foundation for illustrating how we think the system works and for formulating hypotheses that can be tested to improve our understanding. The assumptions and supporting evidence from which we derived this model are provided in the preceding sections of this report and this graphic is simply a means of illustrating many of the important functions and benefits that may be provided by the marine riparian system. This generalized conceptual model is not weighted by any individual function and does not represent the diverse array of marine shorelines found in Puget Sound (e.g., high bluffs, low bank, river mouth estuary). However, it does represent the suite of ecological functions reviewed for this report. It also identifies the need for buffers (i.e., separation zones) that serve to prevent modification of important processes and limit external influences that may impair functions.

Two buffers are identified in our conceptual model: (1) a separation from the water and maintenance of native vegetation to allow for certain functions (e.g., LWD and organic input, pollution abatement), and (2) a separation from the initial buffer to assure that functions are not impaired and will persist for some time. The need for this secondary buffer is identified repeatedly in the scientific literature as an essential component for preserving and maintaining riparian functions. For example, if development (i.e., vegetation clearing, soil compaction, installation of impervious surfaces, introduction of contaminants) occurs up to the edge of the initial buffer, functions may be impaired by overloading the primary buffer (e.g., with sediments, contaminants, noise). This exemplifies the need to recognize both latitudinal and longitudinal connectivity and the establishment of buffers at the appropriate temporal and spatial scales.

Figure 3

Conceptual Model of Marine Riparian Functions



Management Considerations

The current dogma in resource management encourages the incorporation of a watershed perspective in programs dealing with habitat, resource productivity, and conflicts in resource use. Although progressive, the watershed, or catchment basin perspective remains inadequate when considering, for example, how marine and anadromous fishes and wildlife life-history requirements span linkages across terrestrial landscapes and marine/oceanic ecosystems. Therefore, while we attempt to improve our understanding of watershed-scale processes and functions, it is critical that we be mindful of the openness and connections to larger- and smaller-scale ecosystems, levels within ecosystems, and elements that constitute ecosystems. The number and complexity of elements involved in the form and functions of ecosystems can be difficult to understand and often require us to work at a scale that helps us to understand individual elements or ecosystems that are embedded within larger scale systems. In order to do this, we need to identify the pieces to this complex puzzle and determine how they fit. Marine riparian ecosystems are one such piece. Recognizing and developing an improved understanding of marine riparian systems enhances our ability to properly manage natural resources at multiple scales (i.e., local, watershed, landscape) by incorporating previously neglected elements.

This study focuses on riparian functions and marine ecosystem issues in the Puget Sound region. The lack of directed marine riparian studies in this region required a review and assessment of the national and international literature to determine whether studies performed in other coastal regions may be helpful in understanding the importance of individual riparian functions for Puget Sound. Our findings indicate that both freshwater and marine riparian systems serve almost identical purposes, and that marine riparian systems provide additional functions important for supporting marine biota and the integrity of nearshore ecosystems. Unfortunately, the lack of directed studies for defining the full suite of marine riparian functions and values in this region (and elsewhere) leaves much uncertainty and has resulted in a lack of standards and practices to protect riparian systems and other coastal resources.

The recognition of declining coastal resources has never been more apparent and is now acknowledged as a high priority for management by regional, national, and international organizations. We have summarized a representation of these perspectives in the following sections to illustrate the severe reduction in coastal ecosystem services and importance of improved coastal management strategies, which should include recognizing and protecting marine riparian processes, structure, and functions. In addition to perspectives on the status and management of coastal systems, we discuss and summarize the role riparian functions serve, identify data gaps, provide recommendations, and offer some likely outcomes for inadequate consideration of riparian functions in developing coastal management strategies.

Regional Perspective

From a regional perspective, it is clear that substantial losses of marshes and riparian habitat have occurred over the past century in Puget Sound. Estimates based upon evaluation of 11 major deltas in Puget Sound indicate at least a 76% (556 km^2) loss in tidal marshes and riparian habitat (Levings and Thom 1994). Coastal urban areas have lost 90–98% of their estuarine wetlands and water quality is in good condition in only 35% of Washington's estuaries (Washington Department of Natural Resources [WDNR] 1998). Riparian areas within urbanized shoreline areas, such as King County, are approximately 100% altered and are rapidly being further modified or lost as a result of upland development. This is not to say there are not remnants of undeveloped shorelines. Instead, we are referring to the loss of proper functioning conditions from a larger-scale (i.e., landscape) perspective. For example, the fact that a 200-foot stretch of shoreline is not armored and contains native vegetation does not necessarily mean that it is functioning to its fullest capacity. Remnant patches are dramatically influenced by adjacent land use and development practices, which may result in reduced functions at locations that appear to be relatively "pristine."

The difficulty in evaluating the extent of loss, quality of riparian habitat, or level of function stems from the lack of empirical data. Few empirical studies have been conducted because of the lack of recognition, funding, and evaluation of individual or cumulative adverse project impacts. However, recent studies do indicate that the composition of vegetation (i.e., volume, type, age, continuity) and associated functions have been greatly diminished. For example, a survey conducted by Washington Department of Natural Resources (WDNR) in Watershed Resource Inventory Areas 8 and 9 (King County) determined that overhanging shoreline vegetation remained in only 1% and 11%, respectively, along marine shorelines in these areas (WDNR 1999). Additional lessons may be learned from studies of similar ecoregions. For example, May et al. (1997) developed quality indices for lowland streams in Puget Sound as a measure of urbanization impacts on salmon. As the level of basin development increased above 5% of total impervious area (%TIA), results indicated a precipitous initial decline in biological integrity as well as the physical habitat conditions (quality and quantity) necessary to support natural biological diversity and complexity. A wide (>30 m) and near-continuous (<2 breaks/km) riparian zone appears to be necessary although not a wholly sufficient condition for a natural level of stream quality and biotic integrity. Similar inferences can be made when evaluating riparian condition for wildlife needs (see Knutson and Naef 1997). Considering that Puget Sound marine shorelines occur in the same ecoregion as lowland streams (similar geologic history, soils, land-form, vegetation succession, and land-use patterns), we suggest that riparian functions are similar and that the loss of marine riparian vegetation and concurrent increase in impervious area are likely to result in environmental degradation similar to that for lowland streams. Understanding the linkages between landscape or watershed level processes, physical habitat structure, and the organisms that inhabit aquatic ecosystems is a key to successfully managing these resources.

While population growth and development are rapidly diminishing the ability of these urban riparian and estuarine systems to assimilate cumulative human impacts, managing urban estuaries in Puget Sound is constrained by the lack of a scientific foundation for decisions about intervention to improve these degraded systems (Shreffler and Thom 1995). Furthermore, despite growing support from the scientific community, the concept of estuary-wide conservation and restoration planning is constrained by a regulatory process that fosters a fragmented, permit-by-permit approach to ecosystem management. In some cases, activities that result in modifications of shorelines require no environmental review or permits at all. For example, based on the Shoreline Management Act, single family residential (SFR) developments are exempt from shoreline substantial development permits and compensatory mitigation is generally not required for construction projects, such as bulkheads and docks at SFR's (Broadhurst 1998). Single family residential development usually results in significant clearing and grading of shoreline riparian areas for placement of buildings, view corridors, walkways and driveways, landscaping, shoreline armoring, and often, bank stabilization structures (Broadhurst 1998). Residential development along shorelines seldom accounts for natural erosion and often exacerbates erosion potential. In response, bulkheads are frequently constructed, which further disrupts physical and biological processes. While little quantifiable data exist, many researchers and resource managers have observed the linkages between the changes in physical processes and potential impacts to marine biota, such as changes in hardshell clam growth and distribution (Elliffrit et al. 1973), shifts in biotic communities (Antrim et al. 1993, Thom and Shreffler 1994), and loss of feeding habitat for benthic feeding fishes and spawning habitat for forage fishes (Macdonald et al. 1994).

Commercial and industrial development have had similar impacts (see Bortelson et al. 1980, Blomberg et al. 1988). However, as the regional population continues to grow, so will transportation needs and commercial, residential, and industrial development. Despite the fact that larger-scale transportation, commercial, and industrial projects receive a higher level of scrutiny and environmental review, mitigation for impacts is usually incomplete and inadequate. The lack of adequate compensatory mitigation and continued degradation stems from a poor understanding of nearshore ecosystems, a lack of monitoring, a lack of individual or cumulative impact assessment, and the lack of oversight and enforcement of environmental regulations by resource managers (see Kunz et al. 1988, Broadhurst 1998, Lynn 1998).

The protection, restoration, and enhancement of marine riparian areas are of particular importance in the Puget Sound region owing to the fairly recent listings of chinook and chum salmon and bull trout. In February 2000, the National Marine Fisheries Service (NMFS) designated "Critical Habitat" for ESA listed species (chinook and chum salmon). "Critical habitat consists of the water, substrate, and adjacent *riparian zone* of estuarine and riverine reaches....". Critical habitat is designated to include all marine, estuarine, and river reaches accessible to listed salmon in Puget Sound (NMFS 2000). These areas are considered "essential to the conservation of the species" and "may require special management considerations or protection." In consideration of this and other salmon conservation and management guidance (e.g., Spence et al. 1996, NMFS 1996), it is clear that marine riparian areas serve important functions toward the conservation and recovery of salmon stocks in Puget Sound. While we are not suggesting that marine riparian areas be protected solely for the sake of salmon, this designation and definition of critical habitat lends recognition (and possibly credibility) to our argument for recognizing and protecting marine riparian vegetation and associated functions. The National Research Council (2002) has also recognized the importance of riparian systems on marine shorelines and includes these areas in their definition of "riparian."

National and International Perspectives

Marine systems, especially nearshore ecosystems, contain some of the most expansive and productive ecosystems worldwide. Estuaries in particular are the most biologically productive and economically valuable systems in the marine environment. Estuaries are bodies of water 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 the land (Dethier 1990). The unique "mixing zone" of freshwater and saltwater within estuaries derives nutrients from both the land and the sea, forming nutrient-rich, shallow-water habitat that supports abundant fish and wildlife. About 80% of all fish and shellfish worldwide use estuaries as primary habitat or as spawning and nursery grounds. Many species are dependent upon estuaries for their entire life cycle, while others depend upon the protected, nutrient-rich environment for reproduction and early rearing, refuge, and feeding of young. Reproduction success and early survival is critical to the maintenance of valuable fisheries and regional economies. The ecological wealth of estuaries has contributed substantially to the economic wealth of a number of the world's coastal countries. In the United States, home to 28 federally listed "estuaries of national significance," natural resources derived from estuaries contribute approximately $111 billion per year to the nation's economy. As one of the 28 estuaries in the National Estuary Program (NEP), Puget Sound is governed by a comprehensive coastal management plan. The Puget Sound Action Team, a state agency in the Governor's office, oversees the NEP for Puget Sound.

The United Nations Environmental Programme, Chapter 17 of Agenda 21 (as adopted by the Plenary in Rio de Janeiro; United Nations Environmental Programme [UNEP] 1992) states that the marine environment—including the oceans and all seas and adjacent coastal areas —forms an integrated whole that is an essential component of the global life support system. Klaus Toepfer, UNEP Director, noted that the value of marine and coastal ecosystems is equivalent to half of the annual global gross national product, yet we continue to treat coasts and oceans as if they were not an important economic resource. Degradation of the marine environment results from a wide range of sources. Land-based sources contribute nearly 80% of marine pollution, and result from human settlements, land use, construction practices, agriculture, forestry, urban development, tourism, and industry. Many polluting substances originating from land-based sources are of particular concern with regard to the marine environment since they exhibit at the same time toxicity, persistence, and bioaccumulation in the food chain.

A number of federal agencies in the United States (e.g., EPA, NMFS, USFWS, USACOE) have jurisdiction and regulations (e.g., Clean Water Act, Magnuson Fisheries Conservation Act) that recognize and guide management of coastal resources. However, the Coastal Zone Management Act probably provides the most broad-based set of guidelines for protecting coastal resources through land-use practices. The following is from NOAA (1998):

Section 303 of the Coastal Zone Management Act declares that it is the national policy to encourage states to develop and implement management programs to achieve wise use of the land and water resources of the coastal zone. Coastal wetlands (both tidal and nontidal) are among the most productive areas on earth. They are essential habitat for spawning, feeding, and growth of a majority of the nation's living marine resources (Chambers 1991). At the same time, they are among the most stressed natural ecosystems. Since 1780, nearly half of all coastal wetlands, excluding those in Alaska, have disappeared through draining, diking, filling, excavating and other alterations for agriculture, port and urban expansion, and recreational uses such as marinas (Dahl 1990). Stresses on the remaining coastal wetlands are the result of pollutants from nonpoint sources such as farms, forest harvest activities, construction sites and urban areas. Today, coastal zones are most at risk from development pressures brought about by rapid coastal population growth and the demands for housing, transportation, and commercial and recreational facilities (Good et al. 1997).

The coast is home to over half of the nation's population (Culliton 1998), is a popular vacation destination, provides key transportation avenues for over 90% of US international trade (NOAA 1995), and supports over $56 billion in commercial and recreational fishing activity each year (NOAA 1994). The coastal human population is expected to increase by an average of 3,600 per day, reaching 165 million by the year 2015 (Culliton 1998, NOAA 1998). Therefore, finding ways to protect sensitive and valuable coastal resources is imperative.

Bringing this review of issues back to our study area, the Puget Sound region has realized some of the most rapid coastal population growth in recent years and is expected to support continued growth in the coming decades. This will inevitably result in an increasing demand for shoreline development. Living right next to the water is highly valued in our society, but usually results in the clearing of native vegetation for view corridors, buildings, landscaping, and appurtenant structures such as bulkheads and docks. Unfortunately, shoreline development activities have significantly altered the natural structure, functions, processes, and beauty of our shorelines. Much of the historical destruction occurred without regard for the long-term consequences. Furthermore, science and public education have certainly not kept up with the level of development. However, despite the fact that current scientific knowledge and public sentiment support protection of natural resources for a variety of reasons, including aesthetics, existing environmental protection programs have proven to be woefully inadequate and ineffective at stopping the losses.

These perspectives illustrate common themes, including the following:

- Coastal areas are of great economic value due to the productivity and value of natural resources.
- Coastal areas are among the most stressed of natural ecosystems owing to land-use and development practices.
- The health, integrity, and viability of biological resources depends upon the protection and maintenance of natural ecosystem processes, structure, and functions.
- There is a distinct need to provide protection and improve management practices in coastal areas because of the increasing pressures of human habitation and use.
- The recognition of marine riparian functions and benefits, research to better understand marine riparian systems, and the implementation and enforcement of regulations to protect or restore riparian systems are severely lacking.

Conclusions

On the basis of our review of the literature and the application of ecological principles, we conclude that riparian systems perform similar functions regardless of whether the adjacent water body is freshwater or saltwater. Desbonnet et al. (1994) argue that the functional mechanisms that apply to freshwater riparian areas should be similarly applied to marine systems. They point out that marine and freshwater riparian areas serve almost identical purposes, including pollutant removal, soil stabilization, stormwater control, and provision of wildlife and fish habitat. Furthermore, we concur with National Research Council (2002), which states that no justifiable reason exists to exclude shorelines of estuaries and marine coasts in defining riparian areas. It is true that most riparian studies have focused on freshwater (i.e., riverine and wetland) systems. However, studies that have focused on marine shorelines not only support findings similar to those found in freshwater riparian studies, but indicate that additional functions may be linked to marine biota. For example, recent studies in the Puget Sound nearshore ecosystem are finding riparian linkages to salmonid prey production (Penttila 2001, Sobocinski 2003, Brennan et al 2004).

While research and empirical data to quantify functional characteristics of marine riparian systems in Puget Sound are substantially lacking, this review and assessment indicates that marine riparian functions play an important role in marine nearshore ecosystems. Our assessment also indicates that the lack of attention to marine riparian areas and poor protective standards have resulted in substantial loss and degradation of marine riparian and nearshore ecosystem components, which are of value to fishes, wildlife, and human health and safety. There is a critical need to develop and implement a research program and protective standards to learn more about marine riparian systems and prevent further degradation and loss of riparian functions and benefits. This requires identifying data gaps, developing appropriate research questions, dedicating adequate funding and manpower resources, public education and outreach, and the political will to develop, implement, and enforce regulations that are designed to preserve, protect, enhance, and restore riparian functions and benefits. Following this section, a set of recommendations is offered to begin this process.

In conclusion the preceding review provides evidence that indicated the following:

1. A number of riparian functions have critical values and are important for sustaining healthy marine and riparian ecosystems.
2. Marine riparian systems provide a number of ecosystem services that are beneficial to humans, fish, and wildlife.
3. The importance of marine riparian vegetation and associated functions has been recognized at regional, national, and international levels.
4. Increasing human population and development in coastal areas are resulting in the loss of riparian vegetation and adverse effects to the health of marine ecosystems, coastal economies, and human health and safety.
5. The specific requirements for maintaining individual and collective riparian functions and benefits are poorly studied in most areas.
6. Management of coastal areas has been inadequate in protecting natural resources and maintaining ecosystem functions. The shorelines of Puget Sound have experienced significant modifications and continue to be modified.

Recommendations

The science, planning, and policy literature reviewed for this report indicate that much work needs to be done to advance our knowledge and improve management of coastal areas to better protect and restore riparian functions and their inherent values. Human population growth and poorly designed or unregulated development practices have taken a serious toll on marine nearshore resources. Despite recent advancements in science and the development of new educational and management tools, coastal areas, and marine riparian systems in particular, lack adequate protection standards and continue to be degraded. Although Washington State has recognized the ecological importance and social values of shoreline areas (i.e., Shoreline Management Act), marine riparian vegetation and associated functions are not specifically recognized or protected. The following recommendations should be considered as a part of any coastal management strategy and development of shoreline regulations.

Use the Precautionary Principle: "Do No Further Harm"

Two of the most important actions to be taken in natural resource management are to preserve and protect for resource sustainability, values, and services. Until we learn more about the full suite of marine riparian functions, we should rely on existing information and address uncertainty by taking a precautionary approach, providing buffers that protect marine shorelines in Puget Sound from additional degradation. Preserving important riparian areas and preventing additional losses is both critical and cost-effective. Once riparian functions are lost, they are difficult and expensive to restore, if restoration is possible at all.

Fill Data Gaps

Early in the process of identifying and evaluating marine riparian functions, we noticed that empirical data were lacking, particularly for Pacific Northwest coastal ecosystems. This lack of data and limited recognition of riparian functions has led to poor management practices and protection standards for coastal resources. The functions and benefits of marine riparian systems need to be studied and documented in the scientific literature to provide a better understanding of riparian processes and functions relative to nearshore ecosystem integrity. Research and documentation is also critical for establishing a scientific foundation for creating adequate policies and practices for protection and restoration. The following is a list of data needs that would improve our understanding and management of marine riparian systems (adapted from Williams et al. 2001):

1. Determine the role of marine riparian vegetation (MRV) in upland and marine food webs and in energy transfer (i.e., contribution of organic carbon, insects, etc).
2. Determine the role of marine riparian vegetation in providing water quality functions, especially nonpoint source pollution. This will require multidisciplinary investigations of vegetation (type, density, continuity, age structure, etc.), soils, hydrology, and other factors.
3. Identify levels of impervious surfaces (type and extent) in coastal areas and their influence on vegetation, water quality, hydrology, and other riparian processes and functions.
4. Map MRV, including extent (length, width, continuity), type, density, composition, and age structure.
5. Quantify the role of MRV in providing microclimate functions.
6. Quantify the linkages between MRV and important habitat functions for fishes and wildlife that use coastal areas.
7. Conduct additional quantification of the importance of shade and habitat structure to aquatic and terrestrial biota.
8. Quantify the role of MRV and large woody debris (LWD) in increasing slope and beach stability.
9. Determine the cumulative impacts of shoreline armoring and other shoreline development and land-use practices on MRV and MRV functions.

Establish Appropriate Buffers and Setbacks

Buffers and setbacks are essential, functional, and cost-effective tools for preserving important processes and functions, preventing environmental degradation, and protecting valuable coastal resources. Delineating riparian areas and establishing appropriate buffers should be based upon maintaining or reestablishing natural processes and functions in addition to providing for human health and safety and other ecosystem services. This will require scientific investigations that may use freshwater riparian studies as a model for determining functions and benefits. The development of a buffer model would be an important and useful tool for developing buffers.

The scientific support on riparian buffer functions is clear and abundant. There are literally hundreds of articles and dozens of books written on the subject of riparian buffer zones (Wenger 1999). Establishment and maintenance of riparian buffers have long been used to protect wetlands, lakes and streams, but oddly, such buffers are only beginning to be recognized as important marine ecosystem management tools (i.e., within the last decade or so). Although many approaches have been taken in establishing riparian management zones, most set a minimum width with additional setback requirements for steep slopes. Buffer-width considerations should include amount of remaining, intact riparian area along specified reaches of shoreline; impervious surface limitations; and connectivity within and between reaches. As a part of the Tri-County Salmon Recovery Response, a technical workgroup has developed a riparian management zone proposal that might be helpful in developing a management strategy for the State. This proposal recommends both standard and flexible buffers, depending upon the level of urbanization and ability or practicality of buffer implementation.

In Puget Sound, where shoreline retreat is expected (and may occur at an increased rate with sea level rise), wide buffers are needed to allow for wildlife habitat, LWD recruitment, and other functions over time. As in freshwater systems, the functions and benefits provided by the marine riparian zone will vary and be determined by a number of factors (e.g., soils, slope, vegetation type and density). Therefore, determining functional characteristics and associated benefits through empirical studies is critical to establishing appropriate buffer widths. Until we have more empirical data to support marine buffer width determinations, we must rely on models or examples in freshwater systems and take a precautionary approach when developing along marine shorelines to prevent further, irreparable damage.

Maintain or Restore Riparian Vegetation for Human Health and Safety

The discussion of soil stability issues and recommendations for prevention and remediation can be found throughout the technical and non-technical literature (e.g., USEPA 1993, Menashe 1993, Myers et al. 1995; WDOE 1994). From our review of the current literature, it is apparent that maintaining and using native vegetation is a common theme for addressing soil stability concerns. This is particularly true in developing coastal management strategies. Flooding, storm, and erosion hazards are a common problem in coastal areas and become a greater threat when shoreline development does not consider the functions and values of maintaining riparian vegetation buffers (see NRC 2002).

Identify, Evaluate and Incorporate Multiple Functions Into A Management Strategy

Riparian functions and benefits should be evaluated as a whole to define the ecosystem. Management should not be piecemeal and should not be selective for individual functions (i.e., fish prey production, pollution abatement) that may only benefit a select few organisms in the system while ignoring other important ecosystem services (e.g., LWD recruitment, wildlife habitat). Any management strategy should strive to maintain all natural processes and functions, developed through an evaluation of the specific requirements for maintaining individual and collective functions over space and time (e.g., LWD recruitment, life history requirements of multiple species of fishes and wildlife). For marine riparian systems, this will require the use of models, collection of empirical data, and an assessment equivalent to those conducted in freshwater systems.

Use a Multidisciplinary Approach in Developing Riparian Management Zones

The complexity of marine riparian systems and diversity of functions performed by these systems warrant an integrated and multidisciplinary assessment. An appropriate level of analysis will require collaborative efforts from those that specialize in vastly different specialties because riparian systems include terrestrial and aquatic characteristics. Disciplines that should be incorporated include geology, forestry/botany, wildlife and fisheries biology, marine biology, oceanography, soils sciences, chemistry, and hydrology.

Maintain or Restore Riparian Vegetation for Pollution Abatement and Soil Stability

A principle objective of the Clean Water Act (CWA) is to "restore and maintain the chemical, physical and biological integrity of the Nation's waters." Riparian areas serve to meet the goals and objectives of the CWA. Despite efforts to upgrade and expand wastewater treatment facilities, increasing urbanization and destruction of riparian zones will continue to contribute to degraded water quality and are likely to result in increased harvest restrictions and adverse effects to aquatic and terrestrial biota. Knowing that vegetative buffers can provide significant reductions in pollutants, it can be inferred that requiring such buffers would be beneficial by reducing contaminants in runoff and reducing costly reactionary measures to clean up waterways. However, determining appropriate buffer widths to provide pollution abatement functions will require some basic knowledge of environmental conditions (e.g., physiochemical and biological). Maintaining riparian vegetation can be a relatively simple, long-term, and cost-effective method of pollution abatement. Reestablishing riparian vegetation has a cost associated with it, but the long-term benefits are likely to greatly outweigh such costs.

Maintain or Restore Riparian Vegetation for Fish and Wildlife

Because surveys, sampling, and dietary analyses of wildlife, juvenile salmonids, and other fishes in the nearshore environment are limited, additional studies are needed to understand the contribution of riparian vegetation to nearshore food webs, and the impacts of vegetation loss along marine shorelines. Understanding energetic constraints on habitat suitability for fish and wildlife in any system requires a framework capable of determining how nutrient inputs, prey availability, capture success, and other factors interact to produce spatial and temporal variation in growth conditions. Such understanding is sorely lacking for Puget Sound nearshore ecosystems. Therefore, spatially explicit bioenergetics models—which incorporate the spatial distribution of fish and wildlife, their prey, prey production, and the physical conditions that affect foraging and growth—are needed for investigating and understanding the underlying basis for seasonal and spatial differences in habitat suitability (Nislow et al. 2000), habitat selection, and habitat quality. Overall, it is clear that as vegetation is eliminated, the food supply, and thus the carrying capacity of the coastal ecosystem, is reduced.

Protect Marine Riparian Areas from Loss and Degradation

Riparian areas provide a wide range of functions, which are beneficial to humans, fish, and wildlife. These areas provide many ecosystem services to man in the form of pollution abatement, soil stability, improved air quality, recreational and aesthetic benefits, and a wide range of goods and social and cultural values. The health and integrity of the nearshore marine ecosystem depends upon riparian areas because of their location, uniqueness, and functions. Riparian areas are regional hot spots of biodiversity and often exhibit high rates of biological productivity in marked contrast to the larger landscape (NRC 2002). Every effort should be made to preserve remaining marine riparian areas from further degradation, fragmentation, and loss.

Increase Public Education and Outreach

Resource management and protection depends greatly on public perception and participation. As we learn more about marine and riparian systems, it is imperative that the information is translated and transferred to the public. One of the biggest challenges to advancing resource management is changing human behaviors in a manner that will provide protection and reduce degradation and loss of valuable natural resources. Humans will not have an appreciation of and, therefore, will not demand protection for what they do not understand. Consequently, it is critical that decision makers and the general public be educated about the outcomes of their actions, especially those who have the greatest influence on outcomes (i.e., people who live, work, and play along our shorelines).

Develop and Implement Conservation Programs

The development and implementation of conservation programs will be essential for protecting and improving riparian processes and functions in marine ecosystems. Conservation programs may include efforts to preserve, restore, rehabilitate, or enhance existing or lost functions and may also include strategies or actions such as land acquisition, regulatory measures (i.e., setback and buffer requirements), revegetation, and removal of impediments (structures and other modifications of riparian areas). In developing conservation measures, every effort should be made to consider multiple functions and linkages within and between ecosystems. In other words, use ecological principles to guide actions and incorporate multiple functions and processes in developing goals and objectives for conservation actions.

Develop Incentives for Conservation Programs

Conservation programs will only be successful if they take action at the appropriate scales (temporal and spatial) and if they provide incentives for participants. Considering that the majority of Puget Sound shoreline property is in private ownership, state, local, tribal, and federal governments need to create incentives for landowners to change behaviors, or take actions that will protect, restore, or enhance riparian functions. For example, conservation easements are a way to protect riparian areas while allowing the landowner to continue to use their property outside (landward) of the protected riparian area. Land acquisition, tax incentives (i.e., reducing property taxes for not building in the riparian area), providing native vegetation to shoreline property owners for replanting, requiring buffers and setbacks (regulatory incentives), and other measures have also been used and are available for consideration in developing conservation programs. The positive and negative aspects of the various incentives must be considered, but should not exclude them from being used in any shoreline management program.

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