Executive Summary: Overwater Structures: Freshwater Issues

Jose Carrasquero, Herrera Environmental Consultants

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

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

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

This white paper evaluates the state of knowledge of the effects of on-, in-, and over-water structures on the functioning of freshwater ecosystems and their relation to salmonids. Scientific and technical literature on the subject was compiled and examined, and input from experts on freshwater habitats and organism life histories was solicited and evaluated. Effects on an array of organisms and communities were considered.

In order to analyze and present the available data in a logical and easily referenced format, the information sources are divided into either direct or indirect mechanisms of impact, then categorized by the type of response observed.

Three direct mechanisms of impact associated with over-water structures were identified: shore-zone habitat structure changes, shading and ambient light changes, and disruption of water flow pattern and energy. One indirect mechanism of impact associated with construction activities and ongoing operation of over-water structures was identified: physical/chemical environmental disruption (e.g., water quality degradation and noise). Interrelated effects of over-water structure use and operation (i.e., boating activities) are also included under the discussion of this indirect mechanism of impact.

Over-water structures often induce simultaneous responses on predation, behavior, and habitat function, potentially confounding the assessment of any individual response. However, such structures may induce a response in an organism without eliciting a response from its habitat and without promoting a response to its predator-prey system. For this reason and in the interest of clarity, a simple three-part categorization is used here for the range of responses. Under each of the direct mechanisms of impact, available research is grouped into the following categories of response: predation, behavior, and habitat function.

A summary of findings of impacts resulting from changes induced by on-, in-, and over-water structures and associated construction and operation activities is presented under each mechanism of impacts and depicted in flow diagrams. In addition, information gaps are identified and summarized.

Habitat protection, restoration, and mitigation techniques pertaining to the over-water structures and associated activities are analyzed and presented. Also, a summary of the regulatory framework governing over-water structures is included.

Finally, this white paper presents recommendations intended for the development of future policy and guidance documents that address the environmental impacts of over-water structures and associated construction and operation activities.

WHITE PAPER

Over-Water Structures: Freshwater Issues

Submitted to

Washington Department of Fish and Wildlife
Washington Department of Ecology
Washington Department of Transportation

April 2001

WHITE PAPER

Over-Water Structures: Freshwater Issues

Submitted to

Washington Department of Fish and Wildlife
Washington Department of Ecology
Washington Department of Transportation

Prepared by

José Carrasquero
Herrera Environmental Consultants

April 12, 2001

Note:
Some pages in this document have been purposefully skipped or blank pages inserted so that this document will copy correctly when duplexed.

Contents

Figures

Acknowledgments

José Carrasquero of Herrera Environmental Consultants was the primary author of this white paper. Kris Lee, Kittie Ford, Julie Nelson, and Walter Trial, also of Herrera Environmental Consultants, contributed to the literature review effort by gathering information and conducting peer review, and Carol Newlin provided editorial review of the paper. In addition, numerous federal, state, and local biologists and scientists provided valuable published and unpublished information included in this paper.

Larry Fisher, Paul LaRiviere, and Kurt Fresh from the Washington Department of Fish and Wildlife, as well as steering committee members conducted technical review of the draft and provided helpful comments. Also, Doug Pineo of the Washington Department of Ecology, Kitty Nelson of the National Marine Fisheries Service, Tom Kahler of the Watershed Company, and members of the steering committee provided valuable comments during a peer review workshop held in Tacoma, Washington November 6–8, 2000. In addition, Thomas Carlson of Battelle Pacific Northwest National Laboratory provided helpful review of the pile driving section.

Overview of Aquatic Habitat Guidelines Project

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

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

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

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

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

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

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

Assessment of the State of Knowledge

This white paper evaluates the state of knowledge of the effects of over-water structures on the functioning of freshwater ecosystems and their relation to salmonids. Scientific and technical literature on the subject was compiled and examined, and input from experts on freshwater habitats and organism life histories was solicited and evaluated. Effects on an array of organisms and communities are considered.

Although reference to a particular genus is made when appropriate within this paper, all seven native salmon and trout of the genus *Oncorhynchus* (i.e., chinook, coho, chum, sockeye, and pink salmon, and steelhead and cutthroat trout) that occur in Washington are collectively referred to as salmonids.

Predators of salmonids consist primarily of the following species. In lakes of western Washington (particularly Lake Washington and Lake Sammamish), largemouth (*Micropterus salmoides*) and smallmouth bass (*Micropterus dolomieui*) are the juvenile salmonid predators that use shore-zone structures more than other species. In eastern Washington, existing hydrological characteristics of river reservoirs (particularly in the Columbia and Snake rivers) favor the northern pikeminnow (*Ptychocheilus oregonensis*; formerly the northern squawfish) as the major predator of juvenile salmonids (Petersen et al. 1993; Poe et al. 1991; Ward et al. 1995). However, smallmouth bass also have a high potential as juvenile salmonid predators in river and reservoir systems of eastern Washington, particularly in the spring when they inhabit rocky shoreline areas also inhabited by juvenile salmonids (Gray and Rondorf 1986). In this discussion of effects of in-, on-, and over-water structures (hereafter, over-water structures) on predation, the emphasis is on predation of juvenile salmonids by these species.

Methods

Literature Sources

An extensive search of available literature was conducted, including but not limited to the following:

- University of Washington electronic library and commercial databases:
- University of Washington catalogs
- Aquatic Sciences and Fisheries Abstracts (ASFA)
- Water Resource Abstracts (WRA)
- National Technical Information Service (NTIS)
- BIOSIS previews.

The University of Washington catalogs contain over 1.9 million titles held by more than 20 branches of the University of Washington libraries. The ASFA database covers all aspects of marine, brackish, and freshwater environments including biology, ecology; fisheries, aquaculture, oceanography, limnology, resources and commerce, pollution, biotechnology, marine technology, and engineering. The WRA database contains abstracts of journal articles, monographs, and reports covering the development, management, and research of water resources. The NTIS Government Reports is an index produced by the U.S. Department of Commerce, which is a central source for public sale of U.S. government-sponsored research, development, and engineering reports. The BIOSIS previews databases and supplies comprehensive coverage of international life science journals, including references found in biological abstracts.

This review of literature on over-water structures incorporates analysis of existing data available on freshwater organism responses to over-water structures. More specifically, it focuses on the review of studies that address direct and indirect effects of over-water structures and associated construction activities on juvenile salmonids and their habitats. The literature sources include (but are not limited to) peer-reviewed journal articles, theses and dissertations, books, technical documents, previous over-water impact studies in the state of Washington, previous over-water structure impact literature searches, and regulatory documentation. When available, internet web sites that contain information reviewed in this paper are provided. In addition, personal communications with local scientists have been included where related research has yielded pertinent results.

For the purpose of this white paper, sources referring to the ecological effects of over-water structures (i.e., direct sources) are distinguished from literature sources not referring directly to such effects (i.e., indirect sources). Direct sources, then, comprise those references that directly address the mechanism of impacts of over-water structures, as well as those that directly address the response of an organism (particularly juvenile salmonids) to over-water structures (Appendix C). Indirect sources comprise those that address organism predation, behavior, and habitat function without reference to the presence of over-water structures.

During the development of this white paper, a literature review prepared for the City of Bellevue (i.e., Kahler et al. 2000) became available. This literature review was prepared with the collaboration of researchers of the Washington Department of Fish and Wildlife. Also during the development of this white paper, a conference was held to present current and ongoing research on chinook salmon in Lake Washington (i.e., King County 2000). This conference, coordinated by King County, presented research by state and federal agencies. There was some duplication among these three endeavors (i.e., the literature review by Kahler et al. 2000, the conference by King County 2000, and this white paper). Due to time constraints and in the interest of avoiding further duplication, Kahler et al. (2000) and King County (2000) are not fully reviewed in this white paper.

Categorizing Information

In this white paper, unless otherwise stated, only research on over-water structures known to occur in freshwater environments is considered in the literature survey, and the analysis focuses on freshwater environment studies. Appendix B provides a matrix of data availability. A literature review and analysis of the effects of over-water structures in estuarine and marine environments is included elsewhere in the series of white papers and therefore is not discussed here.

Pertinent information on ecological effects of over-water structures (and associated structures and activities) in freshwater environments was found only for the following:

- Docks, piers, boathouses, and floats
- Marinas
- Wharves and pilings
- Log booms and log rafts
- Riprap and retaining walls
- Pile driving and removal
- Construction and operational activities.

This white paper assesses the ecological effects of over-water structures based on the current state of knowledge. In order to analyze and present the available data in a logical and easily referenced format, the information sources are divided into either direct or indirect mechanisms of impact, then categorized by the type of response observed.

For the purpose of this white paper, three direct mechanisms of impact associated with over-water structures have been identified: shore-zone habitat structure changes, shading and ambient light changes, and disruption of water flow pattern and energy. One indirect mechanism of impact associated with construction activities and ongoing operation of over-water structures has been identified: physical/chemical environmental disruption (e.g., water quality degradation and noise). Interrelated effects of over-water structure use and operation (i.e., boating activities) are also included under the discussion of this indirect mechanism of impact.

Over-water structures often induce simultaneous responses on predation, behavior, and habitat function, potentially confounding the assessment of any individual response. However, such structures may induce a response in an organism without eliciting a response from its habitat and without promoting a response to its predator-prey system. For this reason and in the interest of clarity, a simple three-part categorization is used here for the range of responses. Under each of the direct mechanisms of impact, available research is grouped into the following categories of response:

- Shore-zone habitat structure changes
  - Predation
  - Behavior
  - Habitat function

- Shading and ambient light changes
  - Predation
  - Behavior
  - Habitat function

- Disruption of water flow pattern and energy
  - Habitat function.

Objective

The objective of this paper is to evaluate the state of knowledge of the effects of over-water structures on the functioning of freshwater ecosystems within the context of salmonid protection. For this purpose, the following fundamental question is the focus of the review: What are the effects of over-water structures on the ecosystem, measured both by mechanism of impact and by type of response?

Overview of Ecological and Habitat Issues

In general, modification of riparian areas and near-shore littoral zone habitat (i.e., shoreline development) degrades freshwater aquatic communities. Local habitat modification (e.g., construction of individual residential docks) leads to changes in fish assemblages, particularly "when many diverse incremental changes have accumulated within a basin over time" (Jennings et al. 1999).

Cumulative effects of incremental shoreline development on fish assemblages are typically not considered during the construction of a single over-water structure. Years of shoreline development (i.e., construction of over-water structures and associated activities) along lakes, rivers, and reservoirs around the state are now showing the accumulated effects on habitat and fish species. This passage of time has increased the awareness and conviction that cumulative effect analysis is essential to effectively manage the consequences of human activities on the environment (Council on Environmental Quality 1997). However, only recently has the issue of cumulative effects of incremental shoreline habitat modification in freshwater environments been studied (Bryan and Scarnecchia 1992; Beauchamp et al. 1994; Ward et al. 1994; Christensen et al. 1996; Jennings et al. 1999; Lange 1999).

More studies have been conducted on the effects of a range of human activities that alter structural elements of aquatic systems such as size and uniformity of substrate particles (Jennings et al. 1999), quantity and composition of shoreline habitat (Christensen et al. 1996), artificial habitat structures (Beauchamp et al. 1994; Ward et al. 1994), and composition and density of macrophytes (Bryan and Scarnecchia 1992). Among these activities, a high level of concern exists with regard to over-water structures, associated in-water structures, and their related construction activities. This is due to the great potential of these activities to affect, both directly and indirectly, ecological and habitat functions, and thereby individual species.

Jennings et al. (1999) studied the cumulative effect of incremental shoreline habitat modification on fish assemblages in northern temperate lakes. They found that "fish do not respond to shoreline structures: rather, fish respond to various habitat characteristics that are the result of the structures." In addition, fish respond to habitat changes resulting from alterations in the riparian zone (e.g., vegetation and woody structure removal) associated with the placement of the in-water structure (Jennings et al. 1999).

Direct Mechanisms of Impact

Shore-Zone Habitat Structure Changes

Docks, Piers, Boathouses, and Floats

Docks, piers (and pier skirting), boathouses, and floats alter the shore-zone habitat structure, promoting changes in fauna and flora assemblages. These over-water structures can thereby affect the biological community and the environment by altering predator–prey relationships, fish behavior, or habitat function.

Docks and piers are typically structures of open construction that extend into the water from shore (Mulvihill et al. 1980). They come in various shapes, heights, and sizes. They occur in lakes, rivers, and reservoirs throughout Washington and are used for recreational and commercial purposes. They can be pile-supported or supported by a solid base.

A boathouse typically is a building that houses and protects boats. A houseboat is a watercraft with a broad beam, usually a shallow draft, and a large superstructure resembling a house. Houseboats can be either free-floating, anchored on moorages, or supported by pilings. In this regard, one would expect houseboats supported by pilings to have the greatest potential for habitat disruption, because they not only shade the underwater environment but also permanently disrupt the bottom sediments and modify the habitat structure, potentially creating habitat for predatory fishes.

Only two papers were found that address environmental effects of boathouses on aquatic animals and plants (i.e., Brown 1998 and Lange 1999). No literature sources were found addressing the environmental effects of houseboats.

Floats occur in a variety of sizes and shapes, including small moored floating objects (buoys), and larger floating flat objects, known as platforms. Typically, buoys are used for a variety of purposes, for instance, as aid to navigation or for attachment of vessels or instrumentation (Mulvihill et al. 1980). Floating platforms are used for recreational or commercial purposes.

Predation

Predator–prey relations in this section focus on the potential influence of docks, piers, and floats on predation of juvenile salmonids by bass, northern pikeminnow, and piscivorous birds, and by salmonids on their prey. The effects of over-water structures on predator–prey interactions are widely recognized but have not been extensively examined. The literature reviewed does not provide any quantitative or qualitative evidence that docks, piers, boathouses, or floats either increase or decrease predation on juvenile salmonids. No literature source was found addressing pier skirting. No studies have been found examining mortality due to predation specifically associated with over-water structures.

The literature reviewed presents the following observations and inferences:

- Smallmouth bass and largemouth bass have a strong affinity to structures, including piers, docks, and associated pilings.
- Bass have been observed foraging and spawning in the vicinity of docks, piers, and pilings.
- Smallmouth bass are opportunistic predators that consume prey items as they are encountered.
- Smallmouth bass are major juvenile salmonid predators, likely due to the overlap in rearing habitat.

- In the Colombia and Snake river reservoirs, northern pikeminnow is an important predator of juvenile salmonids because of their in-shore preferences and preference for low-velocity microhabitats, which are created by in-water structures.

In western Washington, largemouth bass and smallmouth bass are common predators of juvenile salmonids. Several authors have documented the use of over-water structures by bass in western Washington waters. Stein (1970), examining the types of largemouth bass cover in Lake Washington, found that they prefer areas of heavy log and brush cover over other habitat types (including docks). However, largemouth bass are commonly found under docks in early spring and are thought to be present there until late summer (Stein 1970).

White (1975) studied the influence of piers in Lake Washington and found that fish species (including largemouth bass) are not significantly more abundant (based on catch-per-unit-effort) beneath these over-water structures than at adjacent sites lacking artificial structures. White's (1975) findings led him to suggest that piers provide neither shelter nor habitat for predatory species that prey upon salmonids. However, his sampling method had two major flaws. First, he employed variable-mesh horizontal gill nets as sampling gear, which are more effective for sampling peamouth (*Mylocheilus caurinus*), northern squawfish, and yellow perch (*Perca flavescens*) than for sampling bass. Second, the sampling gear was placed adjacent to the pier rather than beneath it, precluding the characterization of fish composition under the structure. Consequently, the data obtained by White (1975) do not provide information of predatory fish abundance under the piers. In addition, the study sampling gear was ineffective in sampling some fish species, including bass, and therefore, the results do not accurately reflect use of over-water structures by all fish species.

Additional supporting evidence on bass utilization of docks and piers associated with over-water structures comes from unpublished data. Biologists with the Washington Department of Fish and Wildlife found that in local lakes, bass preferentially utilize natural structures, but are also found associated with docks (Kahler et al. 2000). Also, biologists with the Muckleshoot Indian Tribe found that in Lake Sammamish, smallmouth bass preferentially locate their nests near residential piers and associated in-water structures (Kahler et al. 2000). These findings are consistent with the findings of Stein (1970), who observed a largemouth bass affinity for dock, piers, and associated pilings.

Interactions of smallmouth bass and juvenile salmonids depends on factors such as timing of salmonid out-migration, salmonid species, and residence of the juvenile salmonids in lentic or lotic environments (Warner 1972; Pflug and Pauley 1984; Gray et al. 1984; Gray and Rondorf 1986; Poe et al. 1991; Shively et al. 1991; Tabor et al. 1993 and 2000; Fayram and Sibley 2000).

Although substrate type often determines the acceptability of an area for bass spawning, adjacent cover and structural complexity are also necessary for protection while the fish are concentrated in shallow water (Stein 1970; Cooper and Crowder 1979; Helfman 1981b; Pflug and Pauley 1984). Therefore, one would expect that an increase in numbers of docks, piers, boathouses, and floats could be beneficial to the bass population by increasing spawning habitat utilization. Increases in the concentration of bass in spawning sites, where there is an occurrence of juvenile salmonids, may increase the predation on juvenile salmonids. However, researchers have indicated that structural complexity can moderate predator–prey interactions by providing more refuges for prey species as well as reducing the foraging efficiency of the predator (Cooper and Crowder 1979). This moderation may apply to naturally occurring structural habitat complexity, as well as habitat complexity due to the presence of docks, piers, boathouses, and associated pilings. In such a case, fish may adapt to the use of artificial structures in lieu of natural habitats. Prey such as juvenile salmonids, in the absence of natural hiding cover, may use artificial structures as refuge. However, snorkel observations conducted by Roger Tabor in Lake Washington indicate that although they may migrate along the shoreline, passing under docks, the juvenile chinook salmon prefer open areas rather than areas covered by docks (King County 2000). Moreover, although manmade structures can serve as refuge for prey, they may also provide refuge for predators (Cooper and Crowder 1979).

It has been suggested that the increase in the number of docks around the shoreline of Lake Washington might have caused the observed decrease in freshwater survival of juvenile sockeye salmon (Fayram 1996). Studying the spatial location and temporal duration of predation by bass on juvenile sockeye salmon, Fayram (1996) speculates that the increase in docks potentially provides increased locations for bass to ambush prey such as juvenile sockeye salmon while they are in the littoral zone. Fayram (1996) also suggests that the cumulative effect of an increase in predation due to the increase in number of docks may have been great enough to cause the decline in sockeye salmon freshwater survival.

One would expect that the temporal duration of sockeye salmon predation by bass depends on the extent of the overlap of these two species in littoral zones. This overlap may be strongly affected by temperature because, in subyearling fall chinook, temperature appears to control the duration of shoreline residence in Lower Granite Reservoir (Curet 1993). In Lake Washington, the overlap is typically restricted to late April and most of May because juvenile sockeye normally leave the system by the end of May. It is possible that warming of the lake water over time has increased the period of habitat overlap between these two species (Fresh 2000 personal communication). In addition, Vigg et al. (1991) suggests that among the factors influencing consumption rates of smallmouth bass, water temperature is the single most important factor.

The presence of docks and piers may adversely affect existing macrophyte vegetation, potentially altering predator–prey interactions, particularly those in which largemouth bass plays a role. In Lake Baldwin, Florida, largemouth bass showed a significant preference for piers only where aquatic vegetation was absent (Colle et al. 1989). In Lake Sammamish, largemouth bass have been shown to prefer moderate to dense vegetation and silt and sand substrate (Pflug 1981). The preference of largemouth bass for aquatic vegetation habitat may increase their foraging success on passing schools of salmonids, compared with the lesser success of smallmouth bass that occupy habitat with little concealment (Pflug 1981; Helfman 1981b).

Consistent with these findings, Fayram (1996) found that in Lake Washington, largemouth bass are more structurally oriented than smallmouth bass. Floats have been reported to influence the distribution of fish (Crossman 1959; Helfman 1979). Helfman (1979), studying shade-producing experimental floats in Cazenovia Lake, New York, found that several species of predator fishes are particularly attracted to the area under the floats. The author suggests that the large aggregation of prey fishes under floats may also attract predator species, although this is inconclusive in his study. In this study, largemouth bass showed little response, positive or negative, to the presence of floats (Helfman 1979). However, Helfman (1979) observed that largemouth bass occasionally hovered near and below the floats but usually moved away as the diver approached. He speculates that this response to the diver might have biased the data collection process and hence the study results by reducing the numbers of largemouth bass observed at the floats. He also attributes this response to a largemouth affinity for "more massive structure than was provided by the experimental floats." Helfman (1979) did not observe smallmouth bass beneath or near floats, although this species was common in the lake.

The northern pikeminnow (formerly known as the northern squawfish), and to a lesser extent the smallmouth bass, are primary predators of juvenile salmonids in eastern Washington. Existing hydrological characteristics of major river systems have favored the northern pikeminnow as a predator of juvenile salmonids. These hydrological characteristics are the result of a substantial habitat modification, mostly due to the construction of dams. The following quotation from Gray and Rondorf (1989) better illustrates this: "Man has significantly altered the aquatic habitat and fish species complex in the Columbia River, and its alteration has created substantial changes in the dynamics of predator-juvenile salmonid relationships . . ."

During this literature survey, numerous studies of the effects of dams on the ecology and biology of the Columbia basin reservoirs were found, in particular, studies of the effects of dams on salmonid predation. Those studies are beyond the scope of this white paper and therefore are not discussed here. In contrast, only a few studies of ecological effects of in-water and over-water structures in eastern Washington systems were found (Beamesderfer and Rieman 1988; Knutsen and Ward 1991; and Petersen et al. 1993). Such studies show some inconsistencies in the evidence of predatory fish aggregation associated with such structures, and study results show no direct evidence of an increased predation rate on juvenile salmonids. This inconsistency may be due to characteristics of each study site (e.g., fast, free-flowing areas or slow-flowing protected areas) and the species targeted (e.g., northern pikeminnow or smallmouth bass) in each particular study.

Although only a few direct sources have been identified, the following characteristics are all reported to be related to fish predator behavior and distribution in the context of juvenile salmonid predation:

- Degree of habitat overlap (i.e., potential for predator–prey interaction)
- Location in relation to the river mile
- Location in relation to the river stem
- Location in relation to the river flow (i.e., free-flowing or backwater)
- Degree of shore-zone development
- Characteristics of the shoreline (i.e., slope and substrate type)
- Presence of manmade in-water structures (i.e., flow obstructions)
- Species of predatory fishes.

Beamesderfer and Rieman (1988) studied juvenile salmonid predation by northern squawfish and smallmouth bass in a main stem Columbia River reservoir. Beamesderfer and Rieman (19898 conclude that northern squawfish have the greatest potential for predation of juvenile salmonids because of their preference for in-shore low-velocity microhabitat. Low-velocity microhabitat can be created by in-water structures such as jetty pilings (Petersen et al. 1993), but can also be created by dock and pier pilings located along the banks of narrow, fast-flowing sections of the Columbia River reservoirs (Carrasquero 2000 unpublished observation). Therefore, one would expect that resulting low-velocity microhabitats could potentially increase juvenile salmonid predation by providing aggregating habitat for northern pikeminnow and perhaps juvenile salmonids as well.

Additional evidence of predation by squawfish was found by Petersen et al. (1993), who, in a study of the systemwide significance of predation on juvenile salmonids in Columbia and Snake river reservoirs, found that northern squawfish feed primarily on juvenile salmonids. The authors speculate that northern squawfish as well as juvenile salmonids might congregate near flow shears (i.e., back-eddies) created by in-water structures (i.e., jetty pilings), to avoid high-velocity water (Petersen et al. 1993). This preference of northern squawfish for back-eddies has been reported elsewhere (Faler et al. 1988). Consequently, in the Columbia and Snake river reservoirs, in-river obstructions associated with over-water structures such as jetty pilings can make salmonids more vulnerable to predation.

In contrast, Ward et al. (1994) found that developed sites (i.e., sites having floating platforms and pile-supported piers) do not increase predation by northern squawfish. Studying the effect of harbor development on juvenile salmon predation by northern squawfish in the lower Willamette River, Ward et al. (1994) found more northern squawfish in areas without development (i.e., where floating platforms and pile-supported piers are not present).

In terms of understanding the contrasting results, it is noteworthy that the hydrological conditions and shoreline configurations of the sites studied by Petersen et al. (1993) greatly differ from those of Ward et al. (1994). The study sites of Petersen et al. (1993) include free-flowing and high water velocity areas in eastern Washington, with the presence of in-water obstructions and gently sloping littoral terrain. On the other hand, the western Oregon study area of Ward et al. (1994) includes protected harbor areas with low water velocity and steeply sloped bottoms caused by dredging. This difference in study site conditions may help to explain the different results found.

Smallmouth predation on subyearling fall chinook salmon may also be significant in eastern Washington. For example, smallmouth bass accounted for 7 percent of the loss of late-migrating subyearling fall chinook salmon in Lower Granite Reservoir on the Snake River (Anglea 1997). Other research in the Columbia River basin also suggests that smallmouth bass may be a substantial predator of subyearling fall chinook salmon because both species rear in littoral habitat with low water velocities and therefore have a high potential for habitat overlap (Garland and Tiffan 1999; Curet 1993; Tabor et al. 1993).

Shallow near-shore water with a low gradient is an important habitat element for subyearling fall chinook salmon rearing in free-flowing areas of the Snake River. Bennett et al. (1992) reported that areas with low gradients were characteristic of juvenile chinook salmon rearing areas in

Little Goose Reservoir. Similarly, Dauble et al. (1989) found that shallow near-shore areas were preferred by subyearling fall chinook.

Juvenile chinook salmon use of the littoral zone is not unique to eastern Washington systems. In Lake Washington, chinook fry reportedly use shallow shoreline habitat characterized by a sandy bottom and no aquatic vegetation, with an absence of large woody debris (King County 2000).

Tabor et al. (1993), studying smallmouth bass and squawfish predation in the Columbia River, found that juvenile salmonids are the dominant prey item of smallmouth bass, and that crayfish are the dominant prey of northern squawfish. Tabor et al. (1993) also found a habitat overlap (i.e., a near-shore area where current velocities are reduced) between salmonids and smallmouth bass and suggested this as the factor that, when combined with the small size and high abundance of prey, may have contributed to the high salmonid predation rate observed. Smallmouth predation on juvenile salmonids due to habitat overlap has been reported previously (Poe et al. 1991).

Interestingly, Tabor et al. (1993) speculates that "predation on juvenile salmonids may be quite different in free-flowing and adjacent areas from predation in main-stem reservoir areas." If experimentally verified, one may expect this speculation to be consistent with the findings of Petersen et al. (1993). In fact, low incidence of predation on juvenile fall chinook salmon by smallmouth bass in all areas of the free-flowing Snake River already has been reported (Garland and Tiffan 1999).

Also supporting the conclusion of Tabor et al. (1993), Beamesderfer and Rieman (1988) found smallmouth bass more abundant in embayments. This is consistent with previous findings in the Columbia and Snake river reservoirs indicating that smallmouth bass are most abundant in protected embayments (Hjort et al. 1981; Palmer 1982, both as cited by Beamesderfer and Rieman 1988).

Hence, in river reservoirs of eastern Washington, smallmouth bass and northern pikeminnow predatory systems may operate at two different spatial scales, determined by the relative position occupied in reservoirs. These two spatial scales seem to consist of near-shore areas where current velocities are reduced, for smallmouth bass (Tabor et al. 1993), and free-flowing areas with low-velocity microhabitats produced by in-water-obstructions, for northern pikeminnow (Faler et al. 1988; Beamesderfer and Rieman 1988; and Petersen et al. 1993).

As stated earlier, the degree of habitat overlap may affect the rate of predation of smallmouth bass on juvenile salmonids. Studies of habitat use by subyearling fall chinook salmon conducted in reservoirs of the Snake River have shown a subyearling fall chinook salmon preference for littoral habitats. These results have been consistent regardless of the gear type and sampling technique employed (i.e., beach seining [Bennett et al. 1992; Curet 1993] and electrofishing [Garland and Tiffan 1999]).

In terms of avian predation on salmonids, no published data directly pertaining to the effect of over-water structures in freshwater environments were found. (See Phinney [1999] for an overview of avian predation throughout the Yakima River basin and a reference list of Columbia

River studies of avian predation on salmonids.) Nonetheless, a few indirect sources produced some related unpublished data.

Although common in Lake Washington, double-crested cormorants (*Phalacrocorax auritus*) rarely use docks or bulkheads for perching. On the other hand, gulls, also common in Lake Washington, perch on low decks (unpublished data cited by Kahler et al. 2000). Both double-crested cormorants and gulls are known predators of juvenile salmonids.

Cederholm et al. (2000) report that in 1997, a colony of 14,000 Caspian terns (*Sterna caspia*) used Rice Island (a dredge material disposal island) in the lower Columbia River for nesting and roosting, constituting the largest known colony in North America. Their data suggest that in 1997, the terns appeared to be largely dependent on juvenile salmonids for their dietary sustenance (mostly hatchery-originated). Cederholm et al. (2000) also found that although salmon is not their primary diet item, common murre (*Uria aalge*) would use salmon resources during food-stress conditions. In this regard, piscivorous birds are believed to be opportunistic feeders that use the available prey in a system (Modde et al. 1996). No information was found on the use of over-water structures by the Caspian tern or common murre.

Habitat type and location used by fish may determine bird predation success and thereby fish survival. Hence, fish that inhabit pelagic waters (e.g., rainbow trout) are more vulnerable to birds than substrate-oriented fish (e.g., brook trout; Matkowski 1989), because bird predation strategies may be limited by physical characteristics of the habitat such as amount of cover, depth, etc. In this regard, Wood and Hand (1985) found that cover reduces success of capture by one species of bird, the merganser (*Mergus merganser*). Therefore, over-water structures and related construction activities that modify the shoreline configuration (e.g., increasing the shoreline slope and eliminating shallow-water habitat refugia) could potentially affect predation rates on salmonids. This may occur, for example, if the shore-zone habitat and shallow habitat refugia are eliminated, forcing juvenile fish to venture into deeper waters where predator diving birds may have increased success. This hypothetical situation is of particular importance to juvenile chinook salmon, which have the greatest affinity to shore-zone shallow-water habitats (King County 2000; Garland and Tiffan 1999; Fresh 1999 personal communication; Curet 1993; Bennett et al. 1992; Healey 1991; Rondorf et al. 1990; Wydoski and Whitney 1979).

The presence of over-water structures may also influence the distribution of prey items for juvenile salmonids. In Lake Washington, benthic fish food organisms for salmonids, such as insect larvae, amphipods, and mollusks, have been suggested to prefer docks and piers in the absence of aquatic vegetation (White 1975). The presence of benthic organisms, while providing an increased source of food for juvenile salmonids, may also expose the salmonids to increased predation through increased aggregation. This is yet to be demonstrated.

Behavior

No evidence was found to indicate whether docks, piers, boathouses, or floats disrupt the migration of salmonids or cause a delay in migration in riverine systems or in lakes, and no literature sources were found addressing pier skirting. Numerous studies present data suggesting that docks, piers, and floats attract fish, and that this is the main effect of these over-water structures on fish behavior. Anecdotal information from sport fishermen is consistent with these data. Also, it consistently emerged that where vegetation is lacking within a system, largemouth bass populations seek other forms of structures such as dock pilings. Alterations of predator–prey interactions associated with fish behavior that has been modified by human activities are discussed above in the predation section.

Knutsen and Ward (1991) studied waterway development factors (including floating platforms, piers, and associated pilings) and in-river activities (i.e., dredging and construction) with the potential to affect migration rate and distribution of juvenile salmonids migrating through the Portland harbor section of the Willamette River. They found that subyearling chinook salmon occur closer to shore at developed sites than at undeveloped sites. Although Knutsen and Ward (1991) found no evidence that waterway development directly attracts juvenile salmonids or slows migration, they argue that development that causes loss of preferred habitat may have subtle and indirect adverse effects. However, even relatively subtle anthropogenic changes are of concern because of their implications for cumulative effects (see habitat function section below).

Knutsen and Ward (1991) speculate that the amount of time that a particular race of juvenile salmonids spends migrating through Portland harbor might determine the effects of waterway development on their behavior. As juvenile steelhead migrate faster than yearling chinook salmon through Portland harbor, they are exposed to waterway development or activities over shorter time periods (Knutsen and Ward 1991). In addition, because subyearling chinook may be present in Portland harbor during most times of year, in-river activities have more potential to affect this portion of the salmon population (Knutsen and Ward 1991).

Ward et al. (1994) also studied the effects of waterway development on juvenile migration in the lower Willamette River, finding that floating platforms (on a riprap and sand shoreline) and pile-supported piers (on a clay shoreline) have no effect on juvenile salmonid migration. Although Ward et al. (1994) conclude that waterway development presents few risks to migrating salmonids, they recommend that dredging and construction be avoided in the spring when fish are out-migrating, in order to avoid potential construction-related adverse effects.

Several studies indicate that in both eastern and western Washington, juvenile chinook salmon prefer habitats that exhibit the following characteristics (Bennett et al. 1992; Curet 1993; Garland and Tiffan 1999; King County 2000):

- Shallow near-shore habitats with sandy bottom and no aquatic vegetation
- Near-shore shallow water with a low gradient in free-flowing areas
- Littoral habitat with low water velocities.

Hence, juvenile chinook salmon generally are adversely affected wherever these characteristics are modified by shoreline development.

Data from studies conducted in other systems indicate that shoreline development induces behavioral responses in fish. Beauchamp et al. (1994) studied the effect of shore-zone structures (i.e., piling-supported piers and rock-crib piers) on littoral fishes in Lake Tahoe. The piling-supported piers consisted of 20- to 30-centimeter-diameter steel or wood, sunk into the substrate at approximately 5-meter intervals, with a solid deck on top. Piers of this construction provide simple submerged structures lacking complexity. The rock-crib piers consisted of a timber framework, filled with boulders and cobbles, providing habitat complexity in three dimensions (Beauchamp et al. 1994).

Beauchamp et al. (1994) found that piling-supported piers have no significant effect on the densities of any littoral fishes, whereas rock-cribs piers enhance both the density and diversity of fishes in the immediate area. However, this research was conducted at a time when the pier walkways were 2 to 3 meters above water surface and thus provided little or no shade (Beauchamp et al. 1994). The lack of shaded area may have been responsible in part for the low density of fish found, as other authors have shown that fish (particularly prey fish) use shaded areas under docks (Helfman 1979, 1981a).

With regard to fish attraction to shaded areas, Helfman (1979) studied fish attraction to shade-producing experimental floats in Cazenovia Lake, New York. These floats were placed in 3-meter deep water, among dense macrophyte vegetation, although the vegetation was cleared from the area below the floats. Helfman (1979) found that snorkeled-estimated fish densities were significantly higher under the floats than at the control and in adjacent areas, and the densities under floats were positively correlated with the float surface area. In his study, adult golden shiner (*Notemigonus crysoleucas)* and black crappie (*Promoxis nigromaculatus*) were observed near the float, whereas bluegill (*Lepomis macrochirus)* and pumpkinseed *L. gibbosus* were found beneath the float. Although fish were present under the floats during daytime and nighttime, their densities were lower at night and highest at midday, and little feeding activity was seen (Helfman 1979).

In a related study also in Cazenovia Lake, Helfman (1981a) found that the number of fish aggregating beneath shade-producing objects is directly proportional to the size of the objects (i.e., larger floats attract more fishes as more shade is produced). Helfman (1981a) speculates that “the amount (or depth) of shade produced was a determinant of the attraction phenomenon,” which in general may significantly influence the advantage to fish of hovering under such structures. Helfman (1981a) deduces that tactile attraction to the physical structure of the floats is not involved, because fish were not attracted to control floats that consisted of wood frame only. He further indicates that because large numbers of fish were commonly found under docks and under overhanging trees that were supported above the water (i.e., objects located at a fixed height that provide shade without the tactile stimulus), the observed behavior cannot be attributed to tactile attraction.

Consistent with the hypothesis that fish are attracted to the shade produced by on- and over-water structures are recent research data presented during a conference titled *Selected Ongoing and Recent Research on Chinook Salmon in the Greater lake Washington Watershed,* November 8–9, 2000 (King County 2000). The synopsis of findings included data on the factors influencing the decline in all life stages of chinook salmon. These data indicate that migrating adult salmon hold at various locations within the Sammamish River, and that most of these locations are in the shaded area underneath bridges.

The findings discussed in the preceding two paragraphs suggest that the attraction of fish (including chinook salmon and largemouth bass) to floating or overhanging objects is linked to the shade produced by the object rather than to the tactile stimulus. Also, these data suggest that the larger the floating object, the greater the shaded area, and thus the greater the number of fish attracted to such objects, potentially altering fish distribution and aggregation.

An alternative explanation of fish attraction to on- and over-water structures is that both the structures and the shade they cast may provide fishes with physical reference points for orientation (Fresh 2000 personal communication).

In terms of bass habitat preferences in relation to docks and piers, Bryan and Scarnecchia (1992) compared the abundance of juvenile fish assemblages between naturally vegetated sites and developed sites (i.e., with residential structures, boat docks, and manmade beaches) in Spirit Lake, Iowa. Bryan and Scarnecchia (1992) found species richness and total fish abundance (including largemouth bass abundance) consistently greater in natural sites than in developed sites. In contrast, smallmouth bass were consistently found in greater abundance in developed sites.

Studies conducted in Lake Sammamish by Pflug and Pauley (1984) found that smallmouth bass nest sites (located in 1.5 to 2.5 meters of water) were typically situated next to benthic structures such as isolated boulders, logs or dock pilings. Similar results were found by Helfman (1981b) in Cazenovia Lake and Skaneateles Lake, New York, and Mirror Lake, New Hampshire.

Stein (1970) found that in Lake Washington, largemouth bass prefer areas of heavy log and brush cover to all other habitat types, including docks, but often occur under docks in early spring. In Lake Sammamish, largemouth prefer moderate to dense vegetation and silt or sand substrate, and nests are constructed at depths from 0.6 to 1.5 meters, in vegetated areas with soft sediment or gravel substrate on moderate to steep slopes (Pflug 1981). In Cazenovia Lake and Skaneateles Lake, New York, and Mirror Lake, New Hampshire, juvenile largemouth bass also use macrophytes (in depths less than 1 meter) for protection against predators (Helfman 1981b).

The preceding discussion clearly indicates a largemouth bass affinity for aquatic macrophytes, thus posing a question of the implications of removing such vegetation for the construction of over-water structures. The studies discussed below provide some insight into this question.

Colle et al. (1989) studied the distribution of largemouth bass in Lake Balding, Florida after all submerged aquatic vegetation was eradicated by grass carp. Movements of 16 largemouth bass were monitored using radio telemetry from April 11, 1986 to April 4, 1987. A distinct depth segregation was evident for the radio-tagged largemouth bass, which were divided into three groups for purposes of analysis: in-shore (water depth 0–2.0 meters), mid-depth (0–3.5 meters), and offshore (more than 3.5 meters). Colle et al. (1989) found that six largemouth bass had home ranges in the in-shore zone extending 15 to 70 meters from shore. Five largemouth bass used both the in-shore region and the mid-depth region, coinciding with the maximum depth of the blue-green algae in the lake (*Lyngbya* sp). Five largemouth bass used the offshore region. In-shore largemouth bass preferred habitat near a water tupelo (*Nyssa aquatica*) area and avoided bare sand areas. In-shore fish had home ranges averaging 4.1 hectares, whereas offshore fish had home ranges averaging 21 hectares. Largemouth bass that used the entire area out to the 3.5-meter contour preferred the 11 piers in the lake, especially the mid-depth group. Largemouth bass associated with piers moved more than other fish and were associated with multiple piers. Adult largemouth bass using an in-shore fringe of water tupelo as an underwater structure were relatively sedentary (Colle et al. 1989).

Based on these data, Colle et al. (1989) conclude that a component of the largemouth bass population preferred the artificial habitat provided by piers. Colle et al. (1989) suggest that the fact that offshore largemouth bass had a greater home range (i.e., 21 hectares) than the in-shore largemouth bass may be explained by a difference in prey density and structure abundance. That is, prey density was probably lower in the offshore region than in the in-shore region, thereby forcing largemouth bass to shift from ambush to active hunting, because of the absence of underwater structures offshore (Colle et al. 1989).

Both largemouth and smallmouth bass are structurally oriented for both foraging and spawning (Colle et al. 1989; Helfman 1981b; Pflug 1981; Pflug and Pauley 1984; and Stein 1970). They will use docks, piers, and associated pilings in the absence of natural structures. It is not clear which elements of these structures attract them. Additional evidence from published and unpublished data on the behavioral response of bass to docks, piers, and associated pilings can be found in Kahler et al. (2000).

A possible attracting feature of docks, piers, and associated pilings is related to food-web interactions of prey fishes. Chmura and Ross (1978) address the environmental impacts of several in-water and over-water structures, suggesting that as fouling communities grow on docks and piers, they add to the biological productivity of the area (also suggested by Mulvihill et al. 1980). In various rivers and lakes of Washington, it is not uncommon to see fish (including juvenile salmonids) feeding upon periphyton, insects, and macroinvertebrates adhered to dock and pier pilings (Carrasquero 2000 unpublished observation). Thus, associated in-water dock and pier structures that provide substrate for growth of fish food organisms can alter the behavior of both prey and predator species. This is further discussed in the following sections.

Habitat Function

With regard to habitat function, one might argue that the impact of over-water structures is not attributed exclusively to the structure but rather to the resulting changes induced by the structure and associated activities. Within this context it has been proposed that “fish do not respond to shoreline structures; rather, they respond to a suite of habitat characteristics that are the result of the structure, changes to the riparian zone associated with its placement (vegetation and woody structure removal), and often, intensive riparian zone management that occurs on developed properties” (Jennings et al. 1999).

In this white paper, habitat function is defined as the attributes of the ecosystem that are created and maintained by biological, chemical, and physical processes through the interaction of the various ecosystem components (e.g., shore-zone, shoreline, and riparian). Individual habitat modifications may lead to only small changes in local fish species richness, but the fish assemblage structures respond to the incremental changes that accumulate over time within a given basin (Jennings et al. 1999).

In this regard, shoreline development (e.g., construction of docks and piers) in Lake Washington has increasingly eliminated shallow-water habitat (Kahler et al. 2000), particularly affecting juvenile chinook salmon. Once the shoreline is developed, docks and associated pilings may provide shallow-water cover for juvenile salmon, although they may also provide cover for predators (see Cooper and Crowder 1979). Thus, this type of shoreline modification may affect not only the physical habitat but also the various elements of the biological community and the habitat function.

Lange (1999) studied the effects of shoreline residential development on littoral fish abundance (i.e., fish catches) and species richness at different scales of observation (i.e., sampling site distances of 122, 244, and 488 meters) in Lake Simcoe, Ontario, Canada. He found that fish aggregated near permanent rock-crib-supported docks and avoided shoreline areas with bank stabilization structures (i.e., retaining walls built above the ordinary high water line). He also found that in shorelines where multiple features such as docks and break walls were present, fish abundance was positively correlated and species richness negatively correlated with these structures. Features such as docks and break walls combined with boathouses were generally associated with a decrease in both abundance and richness of fish species (Lange 1999).

In addition, Lange (1999) found that shoreline development was associated with sites having hard substrate (i.e., boulder, rubble, and gravel) and an absence of aquatic vegetation. Abundance and richness of fish had a significant positive correlation with both submerged vegetation and the presence of soft substrate types such sand, mud, and detritus, but were negatively correlated with hard substrate types.

Interestingly, Lange (1999) also found reduced fish abundance and species richness with increased density and diversity of shoreline residential development. He found that the specific development features associated with this pattern changed with the scale of observation, indicating that fish respond to both proximally and distantly located habitat alteration.

These results suggest that the cumulative effects of shoreline development might influence fish abundance and species richness. The results also suggest that shoreline alteration can affect fish abundance and species richness regardless of the relative distance of the development from the study site. This clearly illustrates the importance of considering the cumulative effects of even small new residential over-water structures that may be proposed in systems where numerous over-water structures already exist.

Some studies suggest that in the absence of certain predatory species such as bass, piers constructed in shore-zones may have a minimal influence on fish. For example, Beauchamp et al. (1994) studied the effect of shore-zone structures on the density of littoral-zone fishes in Lake Tahoe, California/Nevada. They found that piling-supported piers have no significant effect on the densities of any littoral fish, in contrast to rock-crib piers (i.e., timber framework filled with boulders and cobbles), which actually enhance both the density and diversity of fishes. Beauchamp et al. (1994) suggest that the difference in fish density associated with these two types of piers might be attributed to the greater habitat complexity of rock-crib piers due to the interstitial spaces within the boulders.

Similarly, Lange (1999), studying the effect of shoreline residential development on littoral fishes, found that fish abundance and species richness were higher in rock-crib-supported docks (i.e., permanent docks) than in docks supported by pillars (i.e., seasonal docks).

One may argue that this response should be seen as an adverse effect, because it promotes anthropogenically induced fish aggregation. It is not known whether artificial structures used for habitat restoration in streams actually contribute to the enhancement of the targeted fish species, or whether such structures merely provide a focal point for fish distribution (King County 2000; Beschta et al. 1994; Everest and Sedell 1984; Kauffman et al. 1993; Reeves and Roelofs 1982). A high incidence of failure of artificial habitat structures has been reported for streams of the Pacific Northwest (Fissell and Nawa 1992). Artificial structures that alter fish distribution may increase salmonid predation rates by also aggregating predatory fish. Indeed, to be effective, artificial habitat structures used in restoration projects must be designed with attention to the needs of resident and desired species and consideration of the prevailing physical factors in a particular river or stream (Howe 1997). For example, recent snorkel observations at restoration sites in slow-flowing areas of the Sammamish River indicate that added large woody debris is providing habitat for predatory species rather than for salmon (King County 2000).

Based on qualitative observations of piscivorous fishes in Lake Joseph, Ontario, Canada, Brown (1998) suggested that the presence of predators around crib structures is a response to the abundance of forage fishes. She also studied the influences of shoreline residential development (i.e., docks and boathouses) and physical habitat on fish density in the Lake Joseph littoral fringe zone (i.e., 0–2.5 meters offshore with average depth of 0.53 meters). She found that coarse woody debris (CWD) was the most important habitat variable predicting density of total forage fishes. Sites with the higher number of shoreline structures had the lower densities of coarse woody debris. She also found that crib structures increased densities of forage fishes (<100 millimeters) in the littoral fringe on exposed shorelines or in areas where coarse woody debris had been removed.

Brown (1998) also found that forage fish density in the fringe zone and around shoreline structures increased with the addition of shoreline structures. She attributes this result to the added structural complexity that these structures provide, suggesting that this may increase protection from predators and from physical elements such as wave energy. She speculates that interstitial spaces within crib structures provided refuge from waves and predation for small fish along exposed shorelines.

As noted previously, shoreline development, with its suite of associated human activities and presence of artificial structures, degrades aquatic communities. In the review of habitat function above, individual over-water structures and overall shoreline development are discussed. Bryan and Scarnecchia (1992) studied species richness and juvenile fish abundance (young-of-the-year, YOY) in developed areas (i.e., with docks present) versus undeveloped areas (i.e., naturally vegetated), in Spirit Lake, Iowa. Bryan and Scarnecchia (1992) consistently found greater species richness and total juvenile fish abundance in natural sites than in developed sites in both near-shore and intermediate depth zones (0–1 meters and 1–2 meters, respectively). However, they found little difference between natural and developed sites in the offshore depth zones (2–3 meters). Throughout this study, juvenile fishes were more abundant where macrophyte abundance was greater (i.e., where vegetation was not removed for development). Smallmouth bass was the only species consistently found in equal or greater abundance in developed sites, which Bryan and Scarnecchia (1992) attribute to its lack of reliance on vegetative cover.

Hence, one might expect that if shore-zone development (in particular, construction of docks and associated in-water structures) eliminates the macrophyte vegetation, it might adversely affect fish species assemblages and young-of-the-year survival, particularly of vegetation-dependent species. In this regard, DiCostanzo (1957, as cited by Bryan and Scarnecchia 1992) speculate that insofar as juvenile fish use vegetation beds to avoid predation and to feed during their first summer of life, human activities that eliminate such habitat may reduce juvenile survival.

Collins et al. (1995) compare fish use of fringe zones adjacent to lawns with their use of undeveloped shorelines in Lake Rosseau, Ontario. They found that fish exhibit much less rearing and feeding activity in lawn-edge zones, where wave disturbance is greater, than in undeveloped habitats. Based on their results, Collins et al. (1995) identify shallow water as critical for foraging, refuge, and migration of small fishes (i.e., less than 100 centimeters total length).

Loss of riparian and wetland vegetation resulting from the construction of over-water structures and activities associated with shore-zone development has an adverse effect on water temperature. An increase in water temperature can promote temperature barriers, thus limiting the range and survival of certain fish species (Donald and Alger 1993). Indeed, results of field studies conducted in streams, rivers, and lakes suggest that the distribution and survival of certain species of trout, including bull trout (*Salvelinus confluentus*), are limited by water temperature (Fraley and Shepard 1989; Goetz 1989; Donald and Alger 1993; Rieman and McIntyre 1993; Ratliff et al. 1996; McPhail and Baxter 1996). In general, bull trout are uncommon where water temperature exceeds 15^{o}C for more than a few days per year. In fact, a study of distribution of juvenile bull trout in the upper Cedar River and upper Yakima River drainages found that this species was absent in streams where summer water temperatures exceeded 14^{o}C (Goetz 1997).

Only one source was found addressing benthic communities in the context of the effects of over-water structures. White (1975) studied the influence of shoreline development on fish and benthic fish food organisms in Lake Washington. He found that during the fall, population densities for insect larvae, mollusks, and amphipods were significantly higher outside the piers than under the piers. Conversely, in spring, population densities for mollusks, amphipods, and insects other than Chironomidae larvae (and presumably other grazing insects) were all significantly higher under the piers.

White (1975) suggests that the observed seasonal difference may be due to a combination of factors, including food availability, light, and life histories. The organisms whose partial or complete life cycles are related to aquatic vegetation did not avoid docks during the fall, but rather, responded to the available vegetation outside the docks (White 1975). He attributed the spring preference (for protection, food, and shelter) of areas under docks and piers to the spring vegetation lacking the heavy growth observed during the fall. Therefore, during the spring, the docks offered a viable alternative type of structure to that provided by the vegetation during the fall (White 1975).

In White’s (1975) study, chironomids, an important food item for juvenile salmonids, showed no difference between population densities under and outside the piers. White (1975) did not discuss the potential implication of his results on the survival of juvenile salmonids, particularly juvenile chinook salmon. Interestingly, the samples he obtained from sites without docks ("natural zones") indicated that chironomids were the most abundant organism at these sites. Clearly, his suggestion that docks offer an alternative type of structure to that provided by vegetation does not seem to apply for Chironomidae larvae.

Chmura and Ross (1978) state that “piers, docks, and wharves can have detrimental effects on both salt and freshwater marshes by blocking light and water flow . . . especially if piers are supported by closed (solid) bases.” The associated problem of use of treated wood is also mentioned by Chmura and Ross (1978).

Marinas

As defined by Mulvihill et al. (1980), “a harbor is a protected water area offering a place for safety to vessels. Small craft harbors are protected areas whose depth and maneuvering area limit usage to small craft. ‘Marina’ is used synonymously with small craft harbor, but generally refers to harbors for pleasure crafts.” Although marinas might be seen as over-water structures typical of marine environments, in Washington there are marinas in freshwater environments as well.

During the preparation of this white paper, Kahler et al. (2000) published *A Summary of the Effects of Bulkheads, Piers, and Other Artificial Structures on ESA-Listed Salmonids in Lakes*. This summary provides a comprehensive literature review of published and unpublished data primarily focused on Lake Washington and Lake Sammamish. Although marinas are not explicitly addressed in this review, there is a discussion of the effects of piers, bulkheads, lighting, chemical contaminants, and recreational and construction activities on fish and their habitat, which relates to the potential environmental effect.

Only two papers, both literature reviews, were found that directly address the environmental impact of marinas on freshwater environments (Chmura and Ross 1978; Mulvihill et al. 1980). The Chmura and Ross (1978) paper includes 66 literature citations and is organized by structure type, type of effect, and management considerations. The Mulvihill et al. (1980) paper includes 555 information sources, provides a summary of the literature, and is organized by coastal region case history studies. This review includes environmental impacts and biological impacts, the latter divided by construction, chronic, and cumulative effects. The Mulvihill et al. (1980) review is focused on the impact on the coastal environment and is somewhat outdated, particularly from an environmental viewpoint. Both the Chmura and Ross (1978) and Mulvihill et al. (1980) reviews address issues related to marinas in freshwater, estuarine, and marine environments.

Chmura and Ross (1978) identify both adverse and beneficial impacts caused by marinas. Among the adverse effects, the primary impacts cited are habitat loss, pollution resulting from stormwater runoff, and aesthetic (visual) pollution. Among beneficial impacts, the authors mention concentration of shoreline development ("as opposed to many scattered private docks"), and increased habitat diversity generated where substrate is provided for fouling organisms. Although habitat loss is seen as a primary adverse impact, the authors state that marinas also "provide an artificial habitat with its own unique environment," and that associated in-water structures "can add to the biological productivity of the area and attract fish." While documentation for this statement is not provided, an examination of the Chmura and Ross (1978) reference list suggests that marine or estuarine studies may be the source of this information. Nonetheless, the fish attraction noted by Chmura and Ross (1978) is consistent with the supporting evidence found elsewhere for docks, piers, and floats (see discussion above). However, the Chmura and Ross (1978) review provides no discussion of the potential adverse effect of such fish attraction (i.e., an increase in predation rate).

Dredging is addressed elsewhere in this series of white papers. Therefore, although dredging issues are discussed by Chmura and Ross (1978), only the general adverse effects of dredging associated with over-water structures are listed here:

- Promotion of water turbidity
- Promotion of onsite and offsite pollution
- Reduced oxygen content
- Induced burial of organisms
- Disruption and removal of bottom sediment, and alteration of benthic communities.

The Mulvihill et al. (1980) review provides an examination of the biological and physical impacts of marina placement. Harbors cause loss of benthic succession and impoverishment of substrate and water quality. Furthermore, elimination of wetland areas as productive habitat may result from cumulative effects of harbors constructed in wetland areas (Mulvihill et al.1980).

Wharves and Pilings

Although usually associated with docks, piers, and marinas, wharves and pilings possess their own mechanism of impact on the shore-zone habitat function and structure. Because their effects have been studied for the same categories of response as for docks and piers, some pertinent information discussed in the docks, piers, and floats section above is omitted here.

Empirical indirect evidence indicates predatory fish attraction to pilings and wharves by the following two mechanisms:

- Modification of the underwater habitat complexity, in which case predatory fish are attracted to the physical structure itself (i.e., pilings)

- Physical disruption of the water flow (i.e., back-eddies, backwater, or shear flow), resulting from flow obstruction by such structures.

These two mechanisms seem to be controlled by the shoreline configuration and its degree of natural protection, and also by the hydrological characteristics of the system. The empirical data also indicate a species-specific response of the involved predatory fish. For example, northern pikeminnow is attracted to back-eddies, backwater, or shear flow created by piling structures in free-flowing areas; whereas smallmouth bass is attracted to the piling structure. Some pertinent information in this regard is included above in the discussion of docks and piers and therefore is not discussed here.

Predation

Petersen et al. (1993) found that in the Colombia and Snake river reservoirs, northern squawfish feed primarily on juvenile salmonids and are associated with back-eddies created by jetty pilings. In this regard, Petersen et al. (1993) suggest that in the Columbia River, in-river obstructions below the Bonneville Dam (e.g., pilings) might make salmonids more vulnerable to predation because of the potential for aggregation in back-eddies they create. It is unknown whether this aggregation affects the out-migration rate of juvenile salmonids. Nevertheless, the implication of this behavioral response in terms of increased predation rates on juvenile salmonids may have even more profound consequences on their freshwater survival. This is because juvenile salmonids whose migratory behavior is delayed by aggregating structures may experience increased exposure to predators.

In contrast, Ward et al. (1994), studying the effect of harbor development on juvenile salmon migration and predation by northern squawfish in the lower Willamette River, found that offshore wharves supported by pilings do not have an effect on juvenile salmonid migration. The difference in location between the studies of Petersen et al. (1993) and Ward et al. (1994) may explain these contrasting results. Petersen et al. (1993) focused their study in the Columbia River in an area of free-flowing water in which jetty pilings constitute flow obstructions and create back-eddies. Conversely, the study sites of Ward et al. (1994) are located within a protected area of Portland Harbor in the Willamette River.

As with docks, piers, floats, and marinas, no studies on the effect of pilings and wharves on avian predation were found. Some unpublished data indicate that in Lake Washington, double-crested cormorants perch on individual piles (Kahler et al. 2000).

Habitat Function

Knutsen and Ward (1991) studied the behavior of juvenile salmonids (chinook and steelhead) migrating through the Willamette River at developed sites (i.e., with presence of wharves, pilings, floating platforms, riprap, and vertical walls) and undeveloped sites (i.e., no structure present, and mostly clay, silt, or sand bottoms, steeply sloped from dredging). They report that although there appears to be a species-specific difference between habitat occupied by migrating juveniles at undeveloped sites versus that at developed sites, variables that characterize such habitats seem to have a temporal variation.

To explain, subyearling chinook salmon were found closer to the shore in developed sites than in undeveloped sites, particularly in one site containing a wharf supported by closely spaced pilings (i.e., less than 10 feet apart; Knutsen and Ward 1991). This site had a completely riprapped shoreline and a shallow backwater, with a soft bottom at the downstream end of the wharf. The authors do not specify whether this backwater might have formed as a result of the existing in-water obstructions. However, the downstream location of the wharf and the bottom characteristics suggest that this backwater and associated deposition area (i.e., soft bottom) were at least partially related to the presence of the wharf. Therefore, this, and the fact that at this site the shoreline was completely riprapped, preclude possible inference of the (sole) effect of the wharf.

In general, Knutsen and Ward (1991) found that yearling chinook salmon were closer to the surface than were subyearling chinook salmon at developed sites. Subyearling chinook salmon were found closer to the shore in developed sites than in undeveloped sites. However, results from this study are inconclusive, because the authors are not able to infer whether the observed distribution is related to increased water depth at developed sites or to the presence of developments themselves (Knutsen and Ward 1991).

Nonetheless, one may argue that for future construction, at least the potential physical effect (such as creation of backwater and associated deposition areas) should be considered when placing this type of in-water structure. Increased fine sediments and detritus loading expected to occur in deposition areas such as this could adversely affect bottom-dwelling communities by embedding organisms and promoting anoxic microzones, making bottom habitats unsuitable for benthic organisms.

Although effects of treated wood piling are not addressed within the scope of this white paper, a few of the sources reviewed address this issue as an associated problem of wharves and piling structures. Within this context, two studies are of particular interest: Chmura and Ross (1978) and White (1975).

In their literature review regarding effects of marinas, Chmura and Ross (1978) found that wharves have been reported to be potentially detrimental, through blockage of light and through adverse impacts on water quality (and thereby habitat conditions) due to the treated wood pilings. Also, pilings have been reported to provide suitable substrate for periphyton and some macroalgae species growth (Chmura and Ross 1978; White 1975) and therefore have potential for habitat structure modification.

White (1975) used five experimental pilings (one control, one treated with creosote, one with ammoniacal copper arsenate, and two with pentachlorophenol) to study periphyton attachment in Lake Washington. After one month, diatoms occurred more frequently than other periphyton on all the pilings. The alga, *Cymbella* sp, was the only algal species common to all pilings. The creosote-treated piling had the greatest number of algal species growing on its surface. After one year, all but the ammoniacal copper arsenate-treated piling had extensive algal encrustment, along with many amphipods, limpets, and watermites.

This research suggests that periphyton, algae, and eventually macroinvertebrate species can colonize even treated pilings. Juvenile salmonids as well as other fish species can feed upon these macroinvertebrates species. Therefore, the presence of this source of food on piling surfaces may be a contributing element of distribution of fish prey and thereby fish predators around piling structures.

Log Booms and Log Rafts

The number and body sizes of organisms using the area influenced by a floating object are directly related to the surface area of the object (Helfman 1979, 1981a). Log booms and log rafts are capable of producing a shaded area beneath their surfaces with the consequent potential for altering ecosystem functions. Therefore one would expect a relationship corresponding to that reported by Helfman (1979, 1981a) in relation to the dimensions of log booms and log rafts found in lakes and rivers of Washington. If such a relationship exists, then it is plausible that fish predator–prey interactions similar to those suggested for docks and piers may also exist in response to log booms and log rafts. Unfortunately, no published data were found directly addressing the effects of these two types of on-water structures on fish predation or behavior.

Regarding avian predation, no empirical data were found indicating a relationship between log booms or rafts and predation on fish (nor were data found showing a relationship between these structures and modification of fish behavior [e.g., migration] in freshwater environments). However, log booms have been suggested as potentially linked to avian predation on salmonids by providing perch sites for predatory birds in Lake Washington and Lake Union. In Lake Union, double-crested cormorants perch on the log booms rather than docks, bulkheads, or pilings along the lakeshore (Warner 2000 personal communication, as cited by Kahler et al. 2000).

Habitat Function

Three reports were found addressing the effects of log booms or log rafts in freshwater. Schuytema and Shankland (1976) studied the effects of log handling and storage on water quality and on bottom-dwelling communities at five log-rafting areas. The bottom-dwelling community included “animals” (i.e., insects, macroinvertebrates, and mollusks), “attached algae” (i.e., periphyton), and “slime growth” (i.e., bacteria of the genus *Sphaerotilus*). The study area included Steamboat and Elochoman sloughs on the north side of the Columbia River, about 4 miles downstream of Cathlamet, Washington; Coal Creek Slough on the northern edge of the Columbia River downstream of Longview, Washington; and the western edge of the Multnomah channel, which is part of the Willamette River near Scappose, Oregon.

Schuytema and Shankland (1976) found loss of bark to be the most significant problem associated with log rafting, with effects dependent on the intensity of the activity and the flushing action of the holding water body (i.e., slough, lake, or river). Sludgeworms, which are common inhabitants of areas subjected to organic enrichment or pollution, were consistently present in areas where a high volume of bark occurred (Schuytema and Shankland 1976). In general, they found that the biologically degraded sites identified in the study had fewer kinds of organisms, higher population density, and more bark and detritus.

Schuytema and Shankland (1976) speculate that rafting activities have an adverse effect upon bottom-dwelling organisms in some reaches where log rafts have been present. The decomposition of the log detrital material will "probably produce a habitat more conducive to the establishment of animal populations tolerant to organically enriched conditions" (Schuytema and Shankland 1976). They also found that dissolved oxygen varies with the location depending on the amount of water flow and detritus, and speculate that in areas without adequate water flow (e.g., sloughs), log rafts could adversely affect the population of bottom-dwelling organisms (Schuytema and Shankland 1976).

Schuytema and Shankland (1976) found that dredging to remove the bark was a regularly associated activity of the log rafting sites, and although not discussed in their report, it should be considered as an associated environmental problem of log rafting practices. The implication of dredging in freshwater environments is discussed in a separate white paper within this series.

Similar results have been reported for logs stored in water. Schaumburg (1973) found loss of bark from water-stored logs to be the most significant problem, as benthic depositions exert oxygen demand and may influence the biology of the benthic zone. He also found that leachates from logs held in water storage contained mostly organic substances, and that these substances exerted both chemical and biological oxygen demand. In relatively stagnant areas, the leaching rate continually decreased due to the increased levels of dissolved organic substances, whereas in flowing water the leaching rate was nearly constant for at least 80 days (Schaumburg 1973).

In terms of toxicity, Schaumburg (1973), conducting laboratory toxicity tests, found that leachate from ponderosa pine, hemlock, and older Douglas fir produced no toxicity to chinook salmon or rainbow trout fry during 96-hour bioassay studies. However, log sections without bark were found to be more toxic than comparable sections with bark intact. The 96-hour toxicity test values ranged from 20 to 93 percent (volume/volume) for leachate from young Douglas fir logs. The author speculates that the slight toxicity for young Douglas fir logs may be due to a much greater release of soluble substances into the holding water (i.e., where the fish were held during the test). No information was found addressing bioaccumulation of toxicants and their possible adverse impacts on salmonids.

Based on his findings, Schaumburg (1973) concludes that leachates from logs held in water storage do not represent a significant water quality problem. However he states that "the severity of pollution problems associated with the storage of logs depends upon the quantity of logs stored, the age, and the species of the log and flow rate of the holding water." Unfortunately, this author did not conduct toxicity tests in the field, thereby limiting the applicability of his results to laboratory settings. For example, in storage sites, and under certain physical/chemical conditions of temperature, pH, and dissolved oxygen, log leachate in interaction with naturally occurring substances (e.g., sulfurous compounds) may have additive effects, resulting in a higher toxicity to fish.

Pacific Northwest Pollution Control Council (1971) prepared a literature review of the physical influences of log rafts and their effects on water quality. They found that bark originating from rafting and storage of logs (about 5 percent of each log's bark layer) is a concern because of its potential to increase organic material in the water (see Pacific Northwest Pollution Control Council [1971] for the complete review of related literature and for proposed guidelines and recommendations). A further concern is the long-lasting adverse effects of bark residue in lakes due to the time it may take for its complete biodegradation. For example, within a lake on the Oregon coast that was used for log handling in the early 1900s, the remaining bark residue made habitat unsuitable for several decades thereafter (Pacific Northwest Pollution Control Council 1971).

The primary problems cited by Pacific Northwest Pollution Control Council (1971) associated with bark debris in water are consistent with those cited in the two studies previously discussed. The identified problems related to the accumulation of bark on the bottom are 1) a consequent reduction in dissolved oxygen in the overlying water, and corresponding creation of an anaerobic layer near the bottom, resulting in the generation of toxic sulfide compounds; and 2) burial of benthic communities.

The secondary problem cited by Pacific Northwest Pollution Control Council (1971) is associated with leachates (i.e., release of soluble organic compounds). These leachates are reported to substantially decrease the dissolved oxygen.

Riprap and Retaining Walls

The effects of riprap and retaining walls (i.e., bulkheads) have been broadly studied in marine environments, particularly when used as the means to armor the shoreline for protection against wave-induced erosion (from ambient waves and boat wakes). In contrast, very few sources were found directly addressing the environmental effect of these structures in freshwater environments.

In general, bulkheads are constructed to hold fill and to protect the upland by taking the brunt of wave energy (Chmura and Ross 1978). In doing so, bulkheads prevent natural seepage of groundwater into local waters and create reflection waves which disturb sediments, and encourage scouring at the base of the bulkheads (Chmura and Ross 1978).

The construction of bulkheads promotes loss of terrestrial, shallow-water, and benthic habitat. Such construction involves the use of heavy equipment that causes physical disturbance, noise, and air pollution at the site.

The physical disturbance and damage to fish and wildlife habitat caused by the construction of bulkheads depends upon 1) the type of habitat in the area before construction, 2) the shoreline location where the structure is placed, 3) the size of the structure, and 4) the construction methods. In addition, the bulkhead and associated backfilling bury established terrestrial and shallow-water flora and fauna (Mulvihill et al. 1980).

The construction of bulkheads and associated activities also cause local erosion, new sediment deposits in the vicinity of the structure, turbidity, and hence water quality degradation. New sediment deposits are often silty and thus can destroy spawning areas, smother benthic organisms, and reduce bottom habitat diversity and food supply (Mulvihill et al. 1980).

Bulkheads also promote erosion of the foreshore because of an increase in wave energy due to waves reflecting off the face of the structure. Bulkheads can also promote erosion of adjacent beaches and interfere with sand recruitment processes (Mulvihill et al. 1980).

Bulkheads constructed in wetland areas can cause extensive damage to fishes and wildlife by the following mechanisms: 1) covering narrow fringe marshes, 2) covering the waterfront edge, and 3) altering water circulation in larger shore-front marshes (Mulvihill et al. 1980).

Riprap and retaining walls are typically associated elements of over-water structures that exert a direct mechanism of impact on marine environments. These associated elements are commonly incorporated into dock and pier design as mitigation measures providing permanent erosion control of shoreline areas disturbed by the project construction. However, the empirical data found in this literature review suggest that riprap and retaining walls may produce adverse responses in aquatic organisms.

The following quotation from Jennings et al. (1999) best illustrates the ecological significance of the use of riprap and retaining walls in lakes:

> *Although riprap may increase structure complexity at the scale of the individual site, when viewed at the scale of the whole lake, conversion of the entire shoreline to this one habitat type does not increase overall habitat diversity; rather, it causes a reduction. Because of this reduction of habitat diversity, conversion of unaltered shoreline to riprap should not be viewed as enhancement. However, when erosion control is necessary, riprap appears to provide beneficial fish habitat compared with retaining walls.*

Scientific information on juvenile salmonid ecology from ongoing research indicates that in both western and eastern Washington, shallow-water near-shore habitats are important sites for migration of juvenile salmonids, particularly chinook (King County 2000; Garland and Tiffan 1999; Curet 1993; Fresh 1999 personal communication; Bennett et al. 1992; Healey 1991; Rondorf et al. 1990; Dauble et al. 1989; Wydoski and Whitney 1979). These sites are important because of the abundance of prey resources and refuge from predators. Consequently, loss of rearing and foraging habitat in the shore-zone lentic and lotic freshwater environments may increase juvenile salmonid exposure to potential predators, particularly in freshwater systems such as the reservoirs of the Columbia and Snake rivers, which are used by juvenile salmonids as migratory corridors.

In the context of the effects of shoreline armoring, and comparing retaining wall versus riprap bulkheads, sites next to retaining walls tend to be deeper, primarily because the structures are usually placed below the ordinary high water mark and then backfilled. This effectively pushes the shoreline out from its original location resulting in a corresponding increase in water depth of the littoral zone. Given that, as discussed above, out-migrating juvenile salmonids (particularly chinook) use shallow-water habitats for rearing, foraging, and migration, one may argue that retaining walls may disrupt juvenile salmonid migration. In turn, the cumulative impact of this migration disruption may be an overall reduction in survival rate, as forcing juveniles into deeper water potentially affects their survival by limiting prey resource availability, thereby decreasing their growth rate, and also by increasing their exposure to predators, thereby increasing the predation rate.

Although riprap bulkheads may cause less loss of shallow water habitats than retaining walls, because of the interstitial spaces of their more complex three-dimensional structures, they also may provide concealing habitat to salmonid predators, such as some species of sculpin (Kahler et al. 2000).

Habitat Function

Jennings et al. (1999), studying the relationship between habitat modification and fish assemblage, compared three types of sites in 17 Wisconsin lakes: shoreline modified by the addition of riprap; shoreline modified by the construction of a vertical retaining wall; and unarmored sites. They found that sites with riprap contained more fish species than sites in which retaining walls were constructed and, than unarmored sites. This is because riprap provides more habitat complexity (i.e., interstitial spaces for cover and food production) than retaining walls (Jennings et al. 1999). However, the authors cautioned that their results may have been an artifact of confounding variables (scale of the investigation, heterogeneity of the unarmored sites, and the increased effort required to assess species richness at unarmored sites). Beauchamp et al. (1994) also observed fish preferences for complex habitats in the context of rock-crib piers.

It should be emphasized that although shoreline armored with riprap may provide more habitat complexity than retaining walls, riprap and most manmade structures are not comparable substitutes for naturally occurring structures and aquatic vegetation. The reason may be that from the habitat viewpoint, manmade structures only simulate physical attributes at best, but lack the chemical and biological attributes of, for example, natural wood. Naturally occurring structures such as small and coarse woody debris, as well as aquatic vegetation, possess not only unique physical characteristics contributing to habitat complexity, but also chemical and biological characteristics necessary for healthy food web and predator–prey interactions (e.g., nutrients and substrate for microinvertebrates and food for prey species).

With regard to salmonids, avoidance of armored shorelines rather than aggregation has been reported (Garland and Tiffan 1999). Garland and Tiffan (1999), studying near-shore habitat use by subyearling fall chinook salmon in the Snake River, found that this species avoided bedrock cliffs and manmade boulder (riprap) areas, and was more abundant at sites where sand was the dominant substrate. Key et al. (1996) reported little use of boulders and riprap in a study conducted in the Hanford reach of the Columbia River. Bennett et al. (1992) found most subyearling chinook over sandy substrates in Little Goose Reservoir. Also, Curet (1993) reported that subyearling chinook rearing in Lower Granite and Little Goose reservoirs exhibited a strong preference for sandy areas and showed a moderate avoidance of areas containing cobble. Curet (1993) did not report capture effort over different substrate types. However, because Bennett et al. (1992) and Curet (1993) used beach seine as sampling gear, results from their studies are limited to the areas where beach seining techniques were effective.

As the preceding discussion shows, fish response to riprap varies with the species and geographical area. For example, fish assemblages like those studied by Jennings et al. (1999) in Wisconsin lakes respond to riprap and retaining walls in a different manner than subyearling chinook salmon respond to these structures in eastern Washington reservoirs.

The effect of habitat modification on macroinvertebrate abundance resulting from the addition of riprap and retaining walls has also been studied (Schmude et al. 1998). Using simulated riprap and retaining walls in three Wisconsin lakes, they found that simulated riprap supported greater macroinvertebrate abundance and species richness than did simulated retaining walls, regardless of the shoreline conditions where the simulated structures were placed (i.e., riprap, vertical retaining wall, or natural shoreline). As in other studies discussed above, Schmude et al. (1998) attribute the greater abundance of organisms found in the simulated riprap to the greater habitat complexity that this type of structure provides. They conclude that more complex, three-dimensional artificial substrate associated with riprap, with its greater substrate heterogeneity, surface complexity, and interstitial space, supports a more diverse and abundant macroinvertebrate community in lakes than does the less complex, two-dimensional artificial substrate of the retaining wall. They also speculate that the complexity of erosion control structures (i.e., bulkheads) affects the type and abundance of colonizing macroinvertebrates (i.e., riprap bulkheads support greater abundance).

From the preceding discussion, it becomes apparent that replacement of natural shorelines with simple artificial structures such as retaining walls may reduce the quality of habitat and change the community structure, through the removal of wetland and riparian vegetation and the introduction of changes to physical attributes such as shoreline slope. Removal of wetland and riparian vegetation eliminates fish and wildlife habitat, contributes to the impoverishment of water quality and quantity, and precludes future recruitment of woody debris. In this regard, Ward et al. (1994) found that in the Willamette River, the habitat type used by salmonids at an undeveloped site was unavailable at developed sites, especially at a site where the shoreline had been armored with a vertical retaining wall. They found differences in bottom slopes, water depths, and water current velocities when comparing developed and undeveloped sites.

The simplification of the shoreline (i.e., removal of structure) during the construction of retaining walls further reduces salmonid habitat. This thesis is supported by Christensen et al. (1996), who found that removal of coarse woody debris and shoreline vegetation as a result of bulkhead construction reduced refuge habitat. Christensen et al. (1996), studying 16 lakes in Northern Wisconsin, found a strong negative correlation between riparian snag density and coarse woody debris density and the shoreline cabin density at the whole lake scale. Their results demonstrate that there are substantial impacts of shoreline residential development on littoral riparian snag and coarse woody debris abundance, and that this impact is additive. Christensen et al. (1996) speculate that humans reduce coarse woody debris in lakes, apparently through direct removal as well as by altering riparian vegetation.

However, although most data found during this literature review seem to consistently show the adverse effects of bulkheads, not all of the research results are conclusive. For example, Knutsen and Ward (1991) found that in the Willamette River, physical characteristics of the near-shore zone area did not vary greatly, except when altered by structures. Shorelines associated with structures had steeply placed riprap or vertical walls, and alteration of water depth was commonly associated with waterway developments. The authors found evidence that suggested that water depth might influence the horizontal distribution of yearling chinook salmon and juvenile steelhead. However, the results were inconclusive, and Knutsen and Ward (1991) were unable to find any significant pattern in such distribution for these fish species.

Another inconclusive study is that conducted by White (1975) in Lake Washington. He compared benthic macroinvertebrate abundance at various depths in front of different types of bulkheads, and found that reflected wave action associated with the bulkhead did not displace organisms. However, clear trends of macroinvertebrate abundance were not found, as benthic populations at similar bulkheads often varied, thus precluding any conclusive evidence (White 1975).

Shore-Zone Habitat Structure Changes – Summary of Findings and Data Gaps

Summary

Figure 1 schematically depicts the relationships among impacts resulting from changes induced by on-, in-, and over-water structures and associated construction and operational activities. As illustrated in this figure, on- and over-water structures alter the shore-zone habitat structure, resulting in changes to fauna and flora. Changes in the habitat structure may result in salmonid behavior disruption, which may then affect predation rate. Pile driving and removal and other construction and operational activities cause short- and long-term habitat impacts. Short-term impacts are associated with noise disturbance and water quality impairment during construction. Long-term impacts associated with the presence and operation of the structure may include physical damage to aquatic organisms and a reduction in primary production. Both the presence of structures and the impacts arising from the associated construction and operational activities can disrupt the food web and thereby affect the ecosystem.

The following is a summary of findings of this review pertaining to shore-zone habitat structure changes, organized by the observed type of response.

Predation

- Bass are major juvenile salmonid predators, likely due to the overlap in rearing habitat.

- In reservoir systems of eastern Washington, juvenile salmonid predation is specific to the behavior and distribution of each salmonid species and of its predator. The behavior and distribution of predator and prey species reportedly depend on temperature, the degree of shore-zone development, slope and substrate of the shoreline, and the presence of manmade in-water structures.

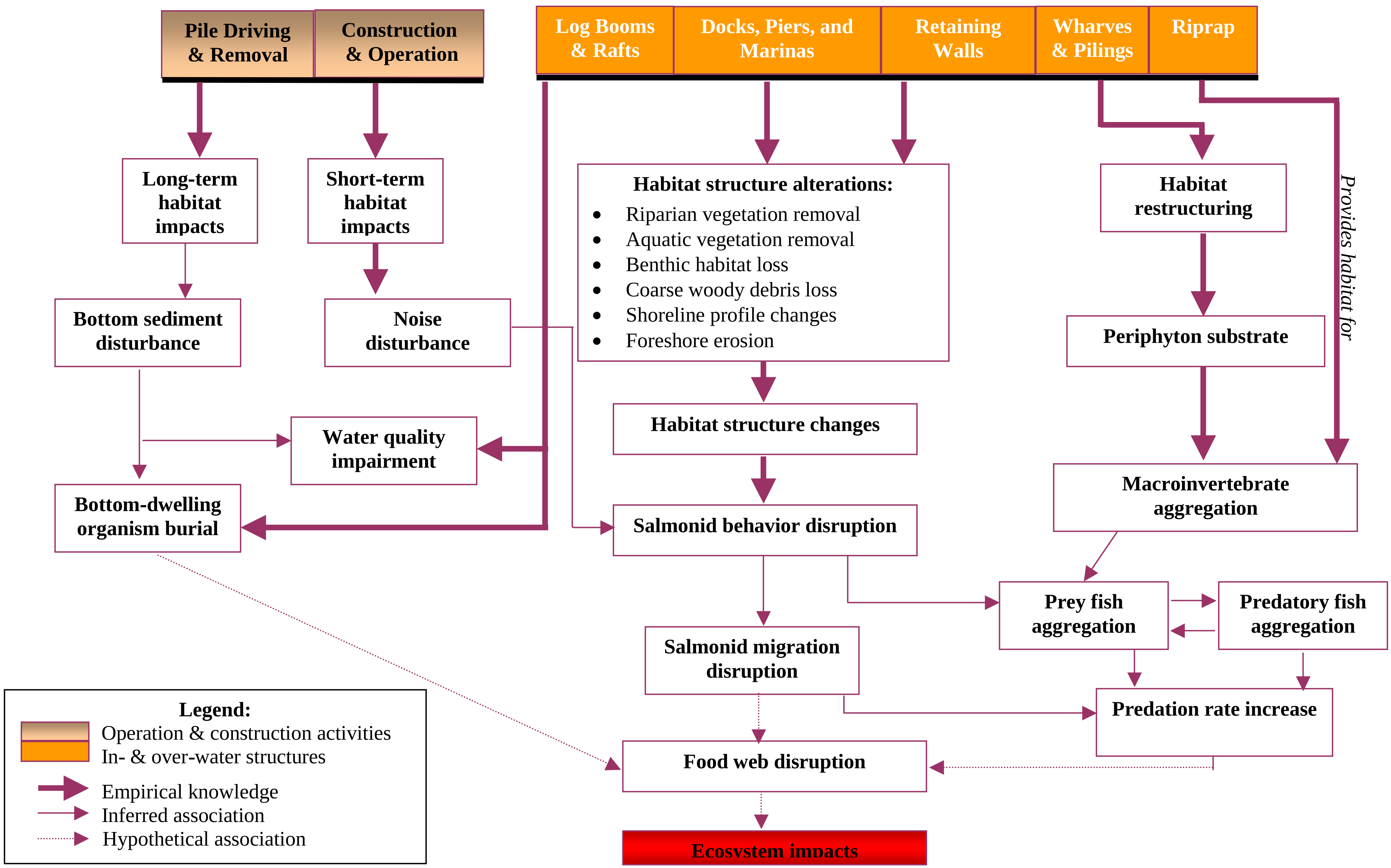

Figure 1. Impacts resulting from changes induced by on-, in-, and over-water structures and associated construction and operation activities.

- In the Colombia and Snake river reservoirs, northern pikeminnow is an important predator of juvenile salmonids because of their inshore preferences and preference for low velocity microhabitats, which are created by in-water structures.

- Habitat used by fish may influence bird prey selection, and in general, cover reduces success of their capture by predatory birds.

Behavior

- Docks, piers, and floats reportedly attract fish, this being the main effect of these over-water structures on fish behavior.

- Over-water structures may affect the survival of organisms (particularly juvenile salmonids) by providing a focal point for predatory fish aggregation, effectively altering predator-prey interactions.

- Although it is not clear which features (e.g., shade, tactile stimuli) of over-water structures attract bass, bass have been observed foraging and spawning in the vicinity of docks, piers, and pilings.

- The shade produced by houseboats and floats versus the shade produced by fixed-height structures may induce different responses in fish.

- Different fish species respond differently to the shade produced by over-water structures.

- Smallmouth bass and largemouth bass have a strong affinity to habitat structures including piers, docks, and associated pilings.

- Fish, particularly largemouth bass, rather than being attracted to the physical structure of experimental floats, seem to be attracted to the shade they produce. In contrast, smallmouth bass do not seem to be attracted to the shade produced by such structures.

- In free-flowing systems, pilings can create back-eddy microhabitats due to the physical disruption of the water flow, thereby attracting northern pikeminnow and perhaps juvenile salmonids to such habitats.

- Bulkheads adversely affect the migration and thereby the survival of juvenile salmonids by diverting them into deeper waters along armored shorelines.

- In the Snake River, subyearling fall chinook salmon avoid bedrock cliffs and manmade boulder (riprap) areas.

- The fish response to riprap and retaining walls varies with the region and the species.

Habitat Function

- The cumulative effects of shoreline development that accompany the construction of over-water structures, may be the main determinant of adverse effects on fish assemblages at the basin level.

- Over-water structures and associated construction and operation activities adversely affect juvenile salmonids by providing habitat for predators adjacent to natural refugia for migratory juvenile salmonids, such as coarse woody debris. Construction and placement of the over-water structures also affect juvenile salmonids by reducing refugia such as coarse woody debris.

- To be effective, artificial habitat structures used in restoration projects must be designed with attention to the needs of resident and desired species and consideration of the prevailing physical factors in a particular river or stream.

- In streams, rivers, and lakes, survival and distribution of salmonids is limited at least partially by water temperature.

- The number and body size of organisms using an area influenced by a floating object are directly related to the surface area of the object.

- Bark originating from log booms and rafts is reportedly the most significant problem associated with log rafting. This is because when bark accumulates on the bottom it may promote 1) a reduction in dissolved oxygen in the overlying water and a corresponding anaerobic layer near the bottom, resulting in the generation of toxic sulfide compounds; and 2) burial of benthic communities.

- The construction of bulkheads causes loss of terrestrial, shallow water, and benthic habitat, and thereby, loss of organisms.

- Bulkheads promote erosion of the foreshore and adjacent beaches, and interfere with sand recruitment processes.

- Due to its greater complexity, riprap reportedly has a greater potential than do vertical walls for maintaining the density and diversity of fishes and macroinvertebrates. However, armoring in general is detrimental to the environment and to organisms.

Data Gaps

No empirical data were found to support several of the processes depicted in Figure 1. Where empirical data are lacking, inferred and hypothetical associations have been drawn. The matrix of data availability in Appendix B shows where data exist for each of the categories of response studied in this white paper (i.e., predation, behavior, and habitat function).

Through this literature review, the following information needs have been identified (organized by the observed type of response):

Predation

- What are the effects of in-, on-, and over-water structures on predator-prey interactions?
- What are the predator-prey behavioral responses to each type of over-water structure and to shore-zone development in general?
- Do the over-water structures affect the predation rate on salmonids or other species? Would changes in design eliminate or minimize the effect?
- Does temperature affect the sockeye salmon and bass habitat overlap in Lake Washington?
- In reservoirs of eastern Washington, does temperature control the duration of shoreline residence of subyearling fall chinook, thereby affecting their habitat overlap with bass?
- What is the effect of over-water structures and shoreline development in general on avian predation?

Behavior

- Are bass attracted to the shade or to the physical structures (or both) of piers, dock, and floats?
- Is the food-web interaction of prey fishes an attracting feature of docks, piers, and associated pilings?
- In free-flowing areas of rivers and reservoirs of eastern Washington, do low-velocity microhabitats increase juvenile salmonid predation by providing aggregating habitat for northern pikeminnow and perhaps juvenile salmonids as well?
- Do on-water structures (e.g., boathouses and log rafts) induce the same effect on the behavior of organisms as over-water structures?

- Why do subyearling fall chinook salmon avoid bedrock cliffs and manmade boulder (riprap) areas in the Snake River? Does this avoidance expose them to increased predation?

Habitat Function

- Do fish respond to the actual shoreline structures, or to the habitat characteristics resulting from riparian zone alterations (e.g., vegetation and woody debris removal) associated with placement of the structures?

- What is the relationship between the cumulative effects of increased number of docks in Lake Washington and the decline in sockeye salmon freshwater survival?

- Can the effects of shoreline development be fully mitigated? How?

- Can habitat function in highly developed shore-zone areas be restored? How?

- In lakes and slow-flowing rivers and reservoirs, does large woody debris enhance salmon habitat or provide habitat for salmon predators?

Shading and Ambient Light Changes

Light is very important in the life of organisms. For juvenile salmonids, light is necessary for orientation, prey capture, schooling, predator avoidance, and migration navigation (Simenstad et al. 1999). Docks, piers, pier skirting, floats, houseboats, boathouses, barges, marinas, pilings, wharves, log booms, and log rafts all shade aquatic habitat and limit ambient light, affecting macrophyte and phytoplankton primary production. This shading could result in a decreased survival rate, or at least promote behavioral changes in various components of the biological community. Lighting associated with these structures may possibly alter fish species behavior, posing increased risk of predation and causing disruption of fish migration patterns. Empirical evidence exists (see discussion below) that indicates that changes in the underwater light environment may have an impact on juvenile salmonid physiology and behavior (Simenstad et al. 1999).

Predation

No data were found supporting a direct link between lighting and an increase in predation of fishes. Research results found were inconsistent, however may provide insight into the effects of lighting associated with over-water structures with regard to increased predation.

For example, under varying light intensities, within the natural range of light intensities occurring at night, it has been shown that predation rates on juvenile salmonids increase with increasing light (Patten 1971; Ginetz and Larkin 1976; Mace 1983, as cited by Tabor et al. 1998).

In contrast, Tabor et al. (1998) in conducting freshwater laboratory experiments found decreased predation rates at higher light intensity. These researchers speculated that rather than increased inhibition of sculpin predatory behavior, the light may have actually influenced salmon behavior, by enhancing the ability of the fry to detect and avoid sculpin, which resulted in reduced predation. Tabor et al. (1998) proposed that differences in study components (such as salmonid species, environment) between their work and earlier studies of Patten (1971) and Mace (1983, as cited by Tabor et al. 1998) may explain the difference in the results they found.

Tabor et al. (1998) in the analysis of their research results, speculated that the reason increased predation did not occur may have been a result of the predator being sculpin, a non-obligated visual fish. In the darkness, sculpin may use some other sensory mechanism besides vision (i.e., their lateral line) to detect prey and therefore, the increase in light intensity may not have enhanced its foraging ability. However, these researches suggested that in the case of visual predatory fish such as cutthroat trout, rainbow trout, juvenile coho salmon, as well as some bird species, increased light intensity might result in an increased predation rate on juvenile salmonids. Consequently, studies using any of these visual species might find an increased predation rate correlated with increased light intensity. The speculation of Tabor et al. (1998) regarding their research results may not be accurate, as other research shows. For example, Petersen and Gadomski (1994) found in laboratory experiments with increasing light intensity a decreasing predation rate between northern squawfish (a visual predator) and juvenile chinook salmon.

In addition to differences in experimental condition, the reason for the lack of consistency in the aforementioned research results may be that simultaneous variables contribute to the effect of potential light-mediated predation rates on juvenile salmonids. In the field, physical/chemical and biological variables may have confounding, interrelated, and simultaneous interactions on fish responses to artificial light associated with over-water structures. To better interpret research results providing indirect evidence of the adverse effect of lighting on fish, such variables need to be studied and further understood. Unfortunately, this is usually difficult, particularly when field experiments are performed.

One example of a physical variable confounding the results of experiments on the effects of light on fish is a study conducted by Vogel and Beauchamp (1999) regarding the effects of light, prey size, and turbidity on reaction distance of lake trout (*Salvelinus namaycush*) and salmonids. They found that with increasing light, reaction distances increased rapidly (i.e., from less than 25 centimeters at 0.17 lux to about 100 centimeters at a light threshold of 17.8 lux). Above this threshold, increasing light contributed no further advantage for prey detection and therefore no further risk to prey. Vogel and Beauchamp (1999) also found that the “reaction distance declined as a decaying power function of turbidity.”

Artificial light associated with shoreline development can also have an effect on predation of juvenile salmonids through the alteration of their migratory behavior. It has been proposed that in the Cedar River, increased artificial light intensity levels may delay fry emigration and cause fry to move to areas of lower water velocity where most predation appears to occur (Tabor et al. 1998). Therefore, one might expect that a delay in emigration due to the increasing incidence of nighttime lighting associated with shoreline development or over-water structures could lead to increased predation on emigrating fry. However, this has yet to be researched.

Behavior

Regarding fish attraction to shade and its potential effect on predation, Helfman (1979) found that in Cazenovia Lake, New York, experimental floats attracted prey fishes (small bluegill and adult golden shiner) and suggested that this aggregation may attract predatory fish species. However, this conjecture was inconclusive in this study. Helfman (1979) speculates that largemouth or smallmouth bass would gain an element of surprise by hovering in shaded regions. Conversely, prey fish would have an advantage by being able to see approaching predators before the predator sees them. This is because floats are shade-producing objects, which reduce the conspicuousness of fish in shade while enhancing their ability to view predators approaching from sunlit surroundings.

As juveniles, predator fish might also seek protection from their own predators by occupying shaded areas. Helfman (1979) speculates that attraction of predatory fish to floats might be because of predator-protection-seeking behavior imprinted as juveniles. Consistent with this, Haines and Butler (1969) show that structures that provide darkness are most often selected by yearling smallmouth bass.

Shade from over-water structures may have effects other than those reported by Helfman (1979) that promote fish aggregation under shade-casting structures. On a species-specific basis, those effects may vary with fish physiology. For example, in their review, Simenstad et al. (1999) analyzed empirical data pertaining to the juvenile salmonid light perception in the context of behavior and physiology. Their review indicates that 1) ambient and artificial light have been reported to induce behavioral responses consistently different between species and ontogenetic stage, and the responses vary with the dispersal patterns of the species; 2) upon a stimulus, the progression of changes the fish eye must undergo from one state to another is influenced by the intensity of the introduced light to which the fish has been exposed; and 3) there are threshold light intensities for different behaviors of juvenile salmonids.

Thus, one may argue that the shade cast by over-water structures that occur over juvenile salmonid migratory corridors may disrupt their migration by creating visual barriers and promoting disorientation. Over-water structures such as docks can create sharp underwater light contrasts by both casting shade and casting light (from lighting) under ambient daylight and nighttime conditions respectively (Simenstad et al. 1999). In this regard, there is empirical evidence which indicates that changes in the underwater light environment will have an impact on juvenile salmonid physiology and behavior, and these changes may pose a risk of affecting fish migration behavior and increasing mortality risk. (See Simenstad et al. 1999; a full review is beyond the scope of this white paper.)

Similarly, it has been suggested that changes in light intensity may modify the behavior of sockeye salmon fry (Tabor et al. 1998). Tabor et al. (1998), conducting simulated stream experiments, found that increased light, especially that above natural levels, appears to slow or stop emigration of fry, which makes them more vulnerable to predation by sculpin. Tabor et al. (1998) found that as light level increased, and in the absence of sculpin, fry emigrated downstream at a slower rate. In the presence of sculpin, fewer fish emigrated but did so at a faster rate than in the absence of sculpin (Tabor et al.1998). Similarly, McDonald (1960) found that the downstream migration of sockeye and coho salmon fry was closely related to light intensity. He found the presence of artificial lights over experimental stream channels at night inhibited the downstream migration of sockeye and coho salmon fry in these channels until the lights were extinguished. Consistent with this finding, Godin (1981), based on a literature review of diel timing of salmon fry migration, indicates that natural light intensity appears to be the major environmental factor controlling the daily onset and termination of the downstream and upstream migrations of salmonid fry. His findings indicate the physiology of these organisms is involved in the process. As changes in the underwater light environment will have an impact on juvenile salmonid physiology (Simenstad et al. 1999), it follows that both the artificial light associated with over-water structures and the shade that these structures produce have a potential for disrupting salmon fry migration and thereby increasing exposure to predators.

In terms of fish attraction to lighting generally, the only data found during this literature review comes from an indirect source (Collis et al. 1995). While conducting an unrelated study on northern squawfish predation on salmonids, Collis et al. (1995) observed that juvenile salmonids were attracted (i.e., surfaced) to work lights in a Columbia River reservoir. However, such attraction may not hold in all systems and for all different ontogenetic stages (Simenstad et al. 1999). In many different second and third order creeks on the Olympic peninsula, night snorkel surveys of juvenile salmonids indicated no attraction to the light produced by flashlights when shined from under the water or from the surface (Carrasquero 1997 unpublished observations). Instead, fry and presmolt salmonids held position, at times even regardless of the proximity of the surveyor.

Habitat Function

In terms of the effects of on-and over-water structures on the light environment, another concern of shading and ambient light changes relates to the potential effects on habitat function. This includes reduction of the ambient light beneath a structure due to light obstruction by an over-water structure (shading), as well as changes of the ambient light (increase in intensity) due to lighting associated with the structure.

As noted previously, shading can affect habitat function by creating visual barriers to migrating fish. The physical design and elements of the over-water structure (i.e., deck height and width, piling numbers and type, pier skirting and batter boards, etc.) can influence whether the shadow cast on the near shore covers a sufficient area and has sufficient intensity to constitute an underwater visual barrier for fish (Simenstad et al. 1999). Also, to the extent that phytoplankton and aquatic macrophytes require light during photosynthesis, over-water structures that reduce or modulate the amount of light will ultimately affect macrophytes beds and reduce phytoplankton primary production, with corresponding effects on habitat function, the food web, and consequently the ecosystem.

Because epibenthic communities depend on light (of certain intensity) to persist, artifacts that may diminish light intensity beneath a structure will affect such communities and their habitat. For example, shading from pile-supported structures may modify wetland habitat, and depending on the amount of shading, algae and aquatic vegetation that occur beneath the structure may be reduced or absent (Mulvihill et al. 1980). However, piling and piers offer substrate for algae to grow in areas where bottom depth is below the photic zone or presents unstable sediment conditions (Mulvihill et al. 1980). A loss of phytoplankton primary production due to shading may be compensated by the primary production of algae that grow on pilings, particularly in areas with bottom conditions as described above.

In this regard, White (1975) studied the light intensity under and outside over-water structures to determine whether structures significantly reduced the amount of light available for primary production of phytoplankton. Not surprisingly, he found that light intensity was higher outside over-water structures compared with intensities beneath the structures, as a result of shading from the structures. However, surface phytoplankton production at the edge of a large over-water apartment complex and under narrow residential piers, exceeded those measured outside over-water structures. White (1975) explains these results as a natural inhibition of production that occurs at the surface of water due to light conditions, which are higher than those in which algae thrive. He suggests that under narrow residential piers, at approximately one meter beneath the over-water apartment complex, light intensity may be reduced to “optimal,” resulting in higher primary production. White (1975) did not study the abundance or distribution of macrophytes under or outside the docks and piers, nor did he investigate the loss of primary production due to the reduction of macrophyte vegetation. Clearly, the loss of macrophyte vegetation due to the placement of over-water structures drastically affects primary production.

In terms of the surface area covered by piers, although suggesting that narrow residential piers do not significantly reduce phytoplankton primary production, White (1975) concludes that there is an inversely proportional reduction in such production due to the reduction of light. White’s (1975) findings that there were no significant reductions of phytoplankton primary production, do not take into consideration the cumulative effects of individual piers. Analysis of alterations occurs primarily at the spatial scale of individual, recreational, and residential properties, the effects are incremental and cumulative in nature (Jennings et al. 1999).

One may argue that a shaded underwater area beneath an over-water structure is essentially a new and different habitat from that which previously existed. This shaded habitat possesses intrinsic physical characteristic that will promote changes in various interrelated parameters such as light intensity, temperature, primary production and consequently, dissolved oxygen (Simenstad et al. 1999). It is expected that the design (i.e., dimensions, materials, and location in relation to the sun path) and flow conditions at the selected site will influence how much such parameters change, due to the shade cast by the over-water structures. In turn, these changes may induce responses in the biological community with ecological consequences, which are still poorly known and much less well understood.

Shade-producing structures can introduce changes to fish assemblages and distributions, which in turn may affect the local communities, and therefore the systems they inhabit. Helfman (1979, 1981a) studied fish attraction to shade producing objects and to experimental floats in Cazenovia

Lake, New York. The experiments were conducted using underwater human observers and cameras. He found the number of fish aggregating beneath shade-producing objects is directly proportional to the size of the objects. Helfman (1981a) suggests that the amount (or depth) of shade produced is a determinant of the observed attraction phenomenon. Helfman (1979, 1981a) concludes that shade, interacting with water clarity, sunlight, and vision, is an important factor in attracting temperate lake fishes to overhead structures. In this regard, the major determinant of the apparent attraction of shade producing objects to fish is the relative visual advantage of a shade versus a sunlit observer (Helfman 1979, 1981a; Helfman et al. 1997). For example, during the day, largemouth bass are typically found near cover, which shields them from high light intensities and may provide a concealed vantage point for the occasional ambush of prey (Helfman 1981a).

The associated problems of shading are not exclusive to docks, piers, or associated piling structures. Floats can also shade the underwater environment in a fashion directly proportional to the site and shape of the structure. However, shaded areas caused by floats are usually small, and therefore a measurable effect is not expected (Mulvihill et al. 1980). No published empirical evidence of the specific effect of floats on habitat function was found.

Shading and Ambient Light Changes – Findings Summary and Data Gaps

Summary

Figure 2 schematically depicts the relationships among impacts resulting from changes induced by on-, in-, and over-water structures and associated construction and operational activities. As illustrated in Figure 2, these structures shade the underwater environment and limit the daylight available for photosynthesis, thus restructuring communities. Construction and operational activities associated with these structures impair water quality and promote algal blooms, thus reducing light penetration and disrupting salmonid behavior. Ultimately, these impacts disrupt the food web and in turn the ecosystem.

The following is a summary of findings of this literature review pertaining to shading and ambient light changes, organized by the observed type of response.

Predation

- In different species and under different environmental conditions, predation rates in juvenile salmonids have been shown to both increase and decrease with increasing light.
- With increasing light, reaction distances increase rapidly but only within a threshold, above which increasing light contributes no further advantage for prey detection. The reaction distance declines as a decaying power function of turbidity.
- Large or smallmouth bass may gain an element of surprise by hovering in shaded regions.

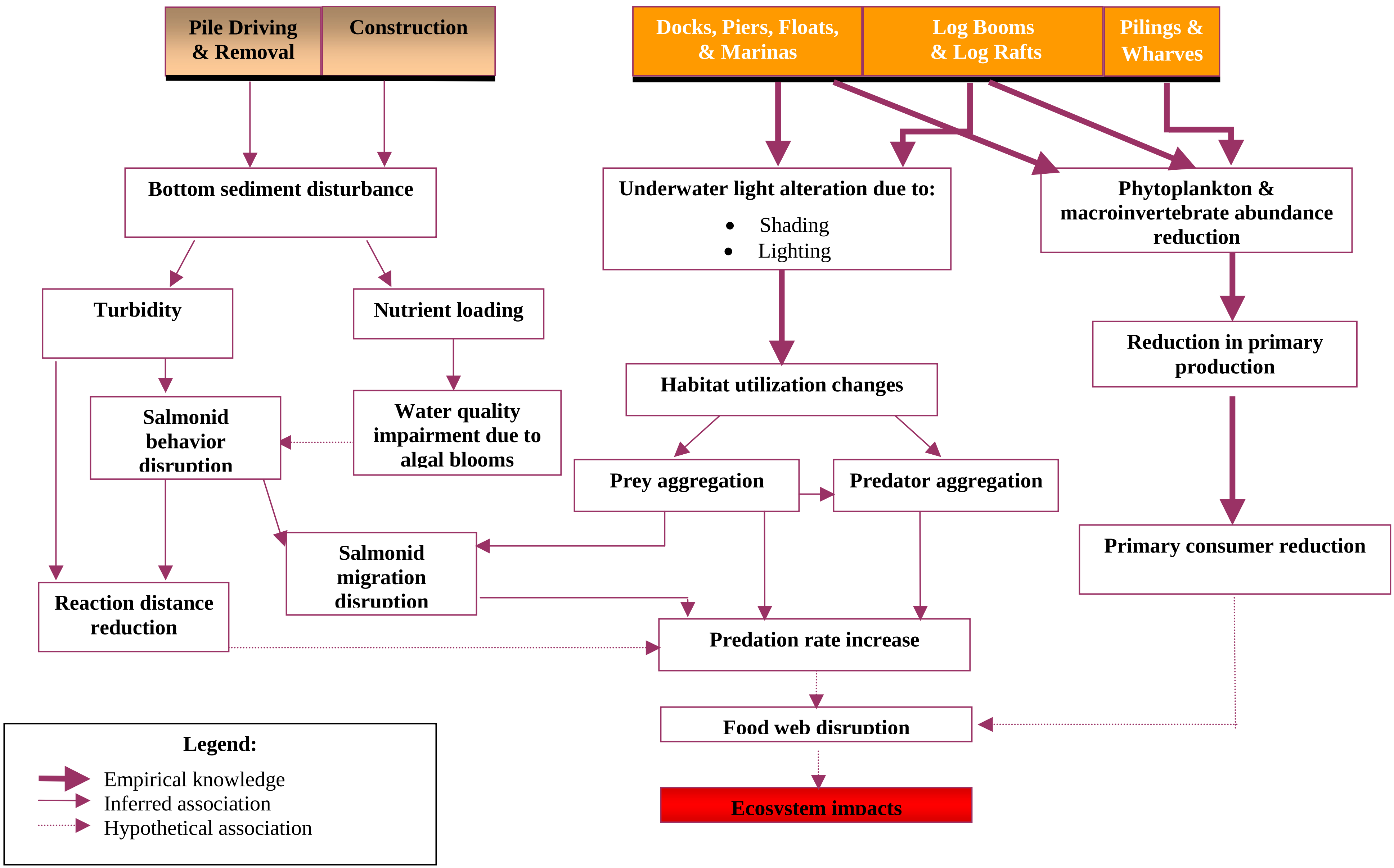

Figure 2. Impacts resulting from changes induced by on-, in-, and over-water structures and associated construction activities.

Behavior

- Ambient and artificial light have been reported to induce consistently different behavioral responses between species and ontogenetic stage, and the responses vary with the dispersal patterns of the species.
- Upon a stimulus, the progression of changes the fish eye must undergo from one state to another is influenced by the intensity of the introduced light to which the fish has been exposed.
- Changes in light in the underwater environment affect juvenile salmonid physiology and behavior. This is because there are threshold light intensities at which different juvenile salmonid behaviors occur.

Habitat Function

- Shading affects habitat function by creating visual barriers to migrating fish.
- Shading from pile-supported structures modifies the water temperature and wetland habitat, and depending on the amount of shading, algae and aquatic vegetation that occur beneath the structure are reduced or eliminated.
- The shade produced by a piling-supported pier promotes a loss of phytoplankton primary production. However, this may be compensated by the primary production of algae that grow on pilings, particularly in areas where the bottom depth is below the photic zone or presents unstable sediment conditions.
- Narrow residential piers may not significantly reduce phytoplankton primary production, but there is an inversely proportional reduction in production due to the reduction of light.
- The cumulative effects of even narrow residential piers are detrimental to the environment.
- Shade interacting with water clarity, sunlight, and fish vision is reportedly an important factor in attracting temperate lake fishes to overhead structures.

Data Gaps

No empirical data were found to support several of the processes depicted in Figure 2. Where empirical data are lacking, inferred and hypothetical associations have been drawn. The matrix of data availability in Appendix B shows where data exist under each of the categories of response studied in this white paper (i.e., predation, behavior, and habitat function).

Through this literature review, the following information needs have been identified (organized by the observed type of response).

Predation

- Is there a relationship between lighting and predation on juvenile salmonids?
- Do large or smallmouth bass gain an element of surprise by hovering in shaded areas under over-water structures?
- What is the relationship between reaction distance decline (due to turbidity) and fish predation rate?

Behavior

- Does lighting from shoreline development and associated over-water structures disrupt or delay juvenile salmonid migration? Would this disruption have an effect on predation on juvenile salmonids?
- What is the relationship between impacts on juvenile salmonid behavior resulting from light changes in the underwater environment and changes in predation rates?
- Do changes in light intensity modify the behavior of sockeye salmon fry? Would this behavior modification make them more vulnerable to predation?
- Do algal blooms originating from nutrient loading disrupt salmonid migration?

Habitat Function

- What are the cumulative impacts of over-water coverage on primary production in various lakes and reservoirs of eastern and western Washington?
- How does the design of structures (i.e., dimensions, materials, and location in relation to the sun path) influence organism responses? Do these responses vary among species or systems?

Water Flow Pattern and Energy Disruption

Docks, piers, marinas, pilings, wharves, riprap, and retaining walls all have the potential to disrupt water flow patterns and energy. This disruption can lead to alteration of the distribution and abundance of sediment, vegetation, and detritus. In turn, alteration of these elements can restructure important habitat features, thereby affecting the biological community.

Docks, Piers, and Floats

Habitat Function

Lorang et al. (1993) studied the effects of lake level regulation and over-water structures on shoreline changes in Flathead Lake, Montana. They characterize two types of systems: 1) reflective systems characterized by dynamic gravel beach faces and steep in-shore shelves armored by wave-washed cobble, and 2) dissipative systems characterized by sand-sized substratum, broad in-shore flat shelves, and the presence of multiple linear bars approximately 350 meters offshore. They also found that piers, which intercept gravel transport, accelerated beach (backshore) erosion on “the downdrift side, and heavy aggregation of migrating gravels occurred on the updrift side.” Erosion on reflective beaches was induced by continuous wave action during the much longer full-pool period (due to lake level regulation), resulting in fore- and back-shore erosion and loss of riparian vegetation (Lorang et al. 1993).

Kahler et al. (2000) speculate that in Lake Washington, which experiences a water level regime similar to that of Flathead Lake, similar processes may occur, with the corresponding effect on riparian and emergent vegetation. They further speculate that gravel interception around shore-zone structures could potentially increase the availability of suitable spawning habitat for smallmouth bass in Lake Washington (Kahler et al. 2000).

Similar processes also occur in reservoir systems of eastern Washington (e.g., the Columbia and Snake river reservoirs; Independent Scientific Group 1996). The fluctuating water levels in those regulated reservoirs prevent the establishment of riparian vegetation. This zone in which riparian vegetation does not become established, called the “varial zone,” includes all the shallow, low-velocity habitats within the river channel of all regulated river segments in the Columbia basin (Independent Scientific Group 1996). Because of such a pattern of water level regulation, one might expect the gravel accumulation process to occur around shore-zone structures, with the corresponding effect on smallmouth bass habitat.

In areas with exposed banks, boat-induced waves moving along the exposed bank at the speed of the boat can erode the slopes, suspending sediments and removing aquatic plants and benthos (Warrington 1999a). Although armoring of the shoreline may be seen as a potential solution, retaining walls, groins, or riprap are not acceptable solutions because these methods often destroy as much habitat as the problems they are designed to treat (Warrington 1999a).

In general, loss of emergent vegetation can promote erosive cycles that preclude the recovery and reestablishment of such vegetation. Erosion of shorelines that cause a decrease in emergent vegetation will also promote changes in sediment transport patterns. This further increases emergent vegetation loss and, in turn, will promote more shoreline erosion (Rolletschek and Kuhl 1997).

Water Flow Pattern and Energy Disruption – Findings Summary and Data Gaps

Summary

Figure 3 schematically depicts the relationships among impacts resulting from changes induced by in- and over-water structures. As illustrated in this figure, over-water structure impacts alter habitat function directly through the loss of riparian and emergent vegetation, and indirectly through shoreline erosion. The loss of riparian and emergent vegetation results in further shoreline erosion, creating an erosive cycle that further increases vegetation loss, with a resultant adverse effect on nutrient cycles. In-water structures alter the water flow pattern, create microhabitats, and disrupt fish behavior, which may affect predator–prey relationships. Both in- and over-water structures can thereby disrupt the food web and thus adversely affect the ecosystem.

The following is a summary of findings of this literature review pertaining to water flow pattern and energy disruption.

- Piers, which intercept gravel transport, may accelerate beach erosion and promote heavy aggregation of migrating gravel. This gravel aggregation, if around shore-zone structures, may increase the availability of suitable spawning habitat for smallmouth bass in such water bodies as Lake Washington.
- In areas with exposed banks, boat waves can erode the slopes, suspend sediments and remove aquatic plants and benthos.
- Loss of emergent vegetation promotes erosive cycles that preclude the recovery and reestablishment of such vegetation.
- Retaining walls and riprap are not acceptable solutions to shoreline erosion, because these methods are often as damaging to habitat as the conditions they are designed to treat.

Data Gaps

No empirical data were found to support several of the processes depicted in Figure 3. Where empirical data are lacking, inferred and hypothetical associations have been drawn. The matrix of data availability in Appendix B shows where data exist under each of the categories of response addressed in this white paper (i.e., predation, behavior, and habitat function).

Through this literature review, the following information needs have been identified (organized by the observed type of response).

Predation

- Does disruption of flow pattern and energy have any influence on predator-prey interactions?
- Do in-water structures that promote fish aggregation by creating slow-flowing-water microhabitats have an effect on the food web?

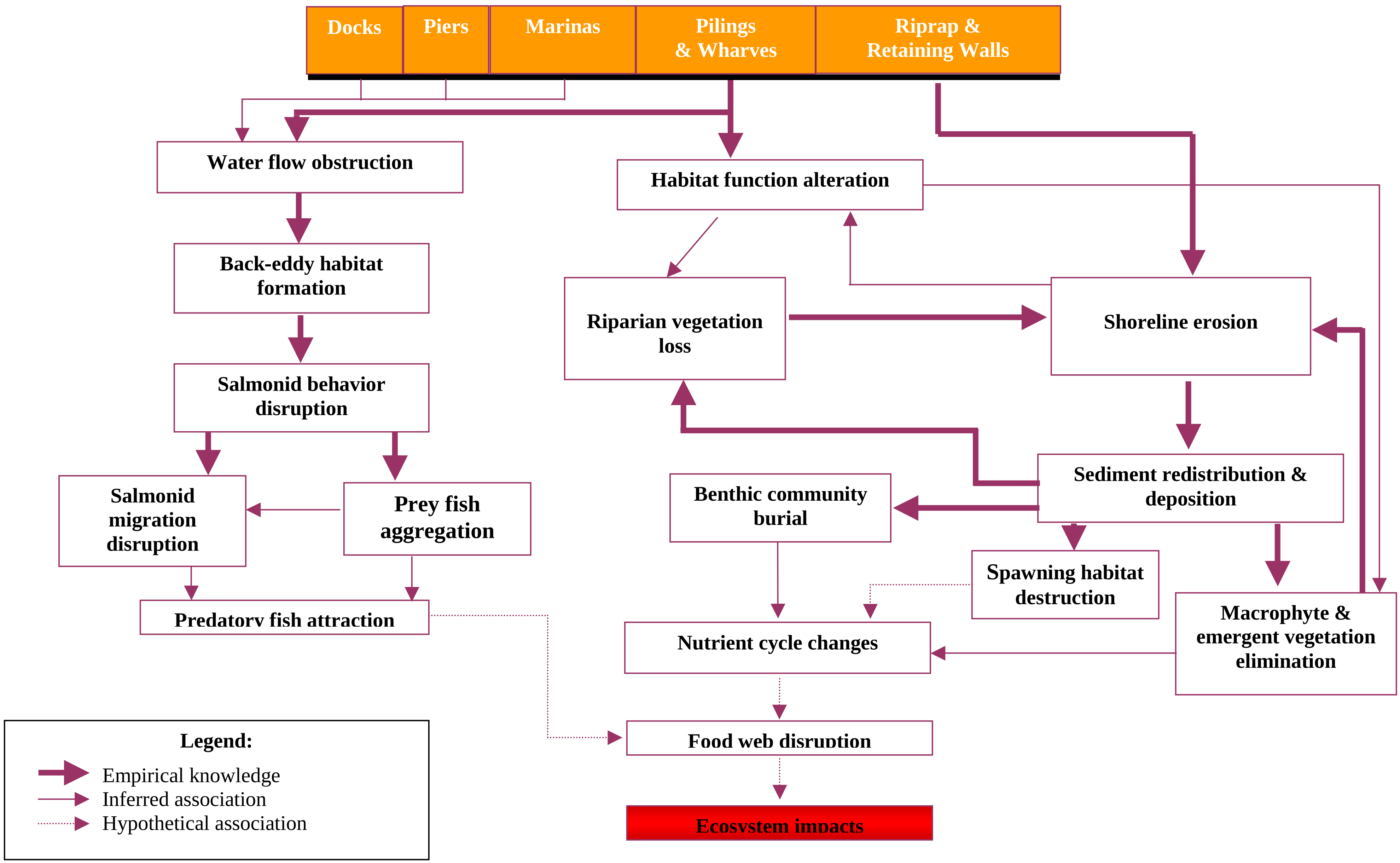

Figure 3. Impacts resulting from changes induced by in- on-, and over-water structures.

Behavior

- What effect does disruption of water flow pattern and energy have on behavior of various aquatic organisms, particularly salmonid fishes and their predators?

- Do in-water structures that disrupt fish behavior affect predator-prey interactions?

Habitat Function

- Does gravel aggregation around shore-zone structures affect bass population density and distribution?

- Are erosive cycles that preclude the recovery and reestablishment of emergent vegetation at work in eastern and western Washington systems? How could they be prevented?

Indirect Mechanisms of Impact

Physical/Chemical Environmental Disruption: Construction and Operation Activities

Although little studied in freshwater environments, the indirect effects of the physical/chemical processes associated with the construction and operation of over-water structures are widely recognized. Chmura and Ross (1978), Mulvihill et al. (1980) and Kahler et al. (2000) all provide literature reviews of direct and indirect effects of over-water structures documented in studies of marine estuarine and freshwater environments. A more comprehensive literature review of the impact of over-water structures on the physical environment can be found in the *Over-Water Structures: Marine Issues* white paper.

Physical/chemical environmental disruption due to construction and operation activities of over-water structures can have both temporary and permanent effects, and are related to noise disturbance and water quality degradation (Chmura and Ross 1978; Mulvihill et al. 1980; Kahler et al. 2000). For example, building an over-water structure involves pulse phenomena during the period of construction (e.g., pile driving, movement of sediments, release of chemicals from building materials), but these stop as soon as, or shortly after, the construction is complete (Underwood 1991). The over-water structure may, however, also cause long-term, possibly permanent adverse changes in such variables as water circulation (flow) and release of sewage or oil from boats. Any of these may cause an adverse environmental response (Underwood 1991).

Pile Driving and Removal

A major cause of disruption during construction of over-water structures is related to pile driving and removal. The effects of pile driving and removal on the habitat and its biological community typically result in localized sedimentation problems, disturbance of pollution-laden sediments, and disruption of normal organism behavior, particularly that of fishes. This can occur through two mechanisms. First, shock waves generated by pile driving may disrupt spawning, rearing, and migratory fish behavior temporarily. Second, pile removal may promote burial of bottom-dwelling organisms and affect water quality by reincorporating pollutants into the water column, making them more readily bioavailable. The latter mechanism can have both temporary and permanent effects.

In general, construction activities (such as pile driving) that disturb the bottom sediments also increase turbidity and can affect bottom-dwelling aquatic organisms, remove submerged aquatic vegetation, drive away fish and other mobile organisms, and alter existing habitat at the structure site (Mulvihill et al. 1980). Turbidity can clog gills of fish and other organisms, and toxic material and silt suspended by construction activities can have a detrimental effect on the biota of the immediate area (Mulvihill et al. 1980). Turbidity effects are most significant for juvenile stages and sessile organisms. In addition, dislodging of organisms can cause spree (i.e., feeding frenzy behavior) by predators during construction periods (Mulvihill et al. 1980).

No freshwater studies showing field data on the effects of pile driving on fishes were found. One published marine study (in Puget Sound) on the effects of pile driving on salmonids was located. However, because underwater sound attenuation due to salinity (i.e., water density) is negligible over the distances of interest at the infrasound frequencies important for salmonid avoidance response, empirical species-specific data from studies conducted in marine and estuarine environments can be extrapolated to freshwater environments (Carlson 2000 personal communication). However, direct extrapolation of data from one species of fish to another is not practicable, because there is a high level of inter-specific variation in hearing capabilities of fishes (Popper 1997). Therefore, results obtained in marine environment studies should be applied to freshwater systems only on a species-specific basis.

For a better understanding of the effects of pile driving on fishes, the paragraphs below summarize the basic principles of underwater acoustics and the structures and function of the fish ear and lateral line, as well as known fish responses to sound. This brief presentation is followed by a review of the published literature on the effects of pile driving.

Sound is defined as a density disturbance that propagates energy through a medium (Popper and Carlson 1998). In water, the energy in a sound wave is contained in the oscillatory movement of water particles and in the pressure that a sound wave originates. Diminution of sound, which results from a decrease in its amplitude due to geometric spreading and attenuation, is a function of distance. Diminution of sound through attenuation is induced by mechanical and chemical factors (e.g., salinity); hence it is also a function of the oscillatory movement of water particles as well as water density (Popper and Carlson 1998).

Fishes detect both the particle motion and pressure components of sound fields using two sensory systems, the ear and the lateral line. Both sensory systems use similar mechanosensory hair cells as transducing structures for signal detection, and both sensory systems respond to similar types of signals (Popper and Carlson 1998). The ear responds to position and acceleration of the body. The lateral line responds to differences between motion of the body and motion of the surrounding water, including stimuli (ranging from less than 1 hertz to several hundred hertz) produced by other swimming fish and other organisms (Popper and Carlson 1998). The ability of fishes to detect the pressure components of sound is species-specific.

Because the body of a fish is about the same density as the surrounding water, density discontinuities are needed within the body for sound detection to occur. These discontinuities consist of the otoliths (in the inner ear) and the swim bladder. The otoliths are at least three times more dense than the rest of the body. The swim bladder undergoes volume changes in a pressure field because it is filled with a compressible medium, thus acting as a secondary sound source in close proximity to hearing structures (Popper and Carlson 1998). This volume change generates a secondary sound field that enables a fish to detect pressure signals with the ear, either through direct coupling with the inner ear or by generating water particle movement (Popper and Carlson 1998; Fay 1997; Sand 1997). However, the efficacy of the swim bladder in exciting the fish ear depends upon the swim bladder's proximity to the ear or direct mechanical connections by fluid-filled ducts, arrangements of bones, or other means. For example, in hearing generalist species such as salmonids, the swim bladder is relatively far from the ear, and enhancement of hearing by the swim bladder appears to be insignificant (Fay 1997; Popper and Carlson 1998). Consequently, salmonids are poorly equipped to detect sound unless they are close to a source where most of the energy in the sound field is carried by pressure.

Wild and hatchery fry and smolts of Pacific salmon and steelhead exhibit an innate avoidance response to infrasound within the frequency range of 8 to 30 hertz (Carlson 1996). The level at which a fish can detect a sound depends upon the level of background noise. The sound must be at least 10 decibels more intense than background noise to be detected; otherwise it is masked by the background noise (Popper and Carlson 1998). Salmonids have a rather poor hearing capability; hence the background noise of the environment (and thereby the masking effect) is not as important in salmonids as in other fish species (Popper and Carlson 1998).

Intense sound (180 to 200 decibels referenced to 1 μPa) can damage the mechanosensory hair cells of fishes. The effect of intense sounds may be more injurious to fish species with highly sensitive hearing (i.e., hearing specialists) such as the northern pikeminnow, and less so to fishes with poor hearing capabilities (i.e., hearing generalists) such as salmonids.

Short-term exposure (for a few minutes) to intense sound may not damage inner ear or lateral line sensory receptors. Consequently, if fishes are able to leave the ensonified area (i.e., the area immediately adjacent to the sound source), their receptors may not be mechanically damaged. Conversely, if fishes remain in the area exposed to strong sounds for extended periods, their receptors may be damaged or some other component of the hearing system may be affected. Nonetheless, sound in general may result in other stress effects, such as decreased growth, increased susceptibility to disease, and impaired reproduction, even in hearing generalist fishes (Popper and Carlson 1998). The effects of intense sound that do not result in easily observed changes in fish behavior or mechanical injury to fishes, such as shearing of hair cells, have not been studied to any extent.

Given that fish eggs and embryos cannot leave the ensonified area, these developmental stages may be adversely affected by sound energy generated by pile driving activities; this has not been studied, however. In this regard, the Washington Department of Fisheries, in a memorandum dated January 13, 1981, recommends a minimum distance needed to protect the eggs of lakeshore spawning sockeye in Lake Washington (WDF 1981). The recommendation consists of establishing a protection area of 300 feet around sockeye spawning sites. This recommendation is based on the analysis of peak energy release and duration data for sound originating from the detonation of explosives during demolition activities.

The energy release during pile driving and detonation of explosives has a short peak period of discharge at which maximum energy release occurs. For pile driving, WDF (1981) estimates that this energy would be measurable within 100 feet of the source. However, pile driving has a relatively longer peak period of discharge than detonation of explosives. Therefore, because the distance at which the energy is felt increases in proportion to the length of the peak discharge, WDF (1981) suggests that the estimate of 100 feet be tripled, and that this new value (i.e., 300 feet) be used to establish the protection area.

It is worth noting that at present sockeye is not the only lakeshore spawner that occurs in Lake Washington. In recent years, chinook salmon have been observed spawning in lakeshore areas of Mercer Island and Lake Union (Fisher 2000 personal communication; Quinn 1999 personal communication; Kinnison 1999 personal communication). Therefore, in Lake Washington, the concern regarding potential pile driving impacts on fish eggs and embryos also applies to this species.

Carlson (1997) characterizes the underwater sound generated by impact pile driving within the context of the response of salmonids to impulse sound, and concludes that the sound thus produced is unlikely to significantly affect the migratory behavior of salmonids. These studies were conducted over a two-day period at a pile dike repair where 15 piles were replaced on the Washington shore of the Columbia River upstream of Altoona, Washington. All underwater sound measurements were made within 30 feet of the piles being driven and at one of four depths (i.e., 5, 10, 15, or 20 feet). Sound measurements were obtained near the surface, at mid-depth, and at the bottom.

Based on his findings, Carlson (1996) concludes that impact pile driving does not produce adequate stimuli for sustained avoidance responses in salmonids. The reason is that in salmonids, the effective stimulus for avoidance response is the local flow (i.e., particle displacement) component of infrasound in the range of 5 to 30 hertz where water particle acceleration is less than 0.01 ms^{-2} (meters per second per second). At this sound level, water particle motion is found only in the near-field of volume displacement sources capable of generating an intense local flow field (Carlson 1996). In short, salmonids would have to be very close to the noise source to be disturbed and express an avoidance response. The threshold distance for an avoidance response by salmonids has been experimentally determined to be approximately 10 feet.

In another study, Carlson (1996) characterizes the underwater sound generated by vibratory pile driving within the context of the characteristics of sound known to result in avoidance response by juvenile salmonids. His experiments consisted of the comparison of data collected during vibratory pile driving operations against model data obtained from a volume–displacement–

infrasound source. The study was conducted during vibratory driving of six piles along the outer perimeter of a pier at the Hatfield Marine Science Center in Oregon.

Carlson (1996) found that infrasound generated by vibratory pile driving is not continuous and has a short life span but is probably dependent upon various aspects of the pile driving activity. Such aspects include the design and mode of operation of the vibratory hammer, the characteristics of the piles being driven, and characteristics of the substrate into which the piles are driven. For all of the piles observed, most of the energy in the sound field was located at frequencies below 50 hertz, with approximately half at infrasound frequencies. Results showed that vibratory pile driving generates a sound field with considerable energy in the frequency range where salmonid avoidance has been observed (Carlson 1996).

Carlson (1996) concludes that the vibratory pile is unlikely to cause an avoidance response by juvenile salmonids beyond the immediate vicinity of the pile driving activity. In addition, this type of construction activity is, in general, unlikely to have a significant impact on migrating salmonid behavior, because "generation of water particle motion levels in excess of fish behavioral response thresholds appears unlikely at ranges over 20 to 30 feet from the pile being driven" (Carlson 1996).

Regarding the published marine study on the effects of pile driving on salmonids, Feist et al. (1996) studied the effects of impact and vibratory pile driving on the behavior of juvenile chum and pink salmon in Puget Sound. They determined that salmonids could detect the sound of impact pile driving within a radius of at least 600 meters, and that the sound was at least 20 decibels above ambient levels at 593 meters. The pile driving did not cause juvenile chum and pink salmon to change their distance from shore or to cease foraging activities. However, Feist et al. (1996) found that the distribution and sizes of fish schools, and behavior within schools, on pile driving days significantly differed from that on non-pile-driving days.

It should be noted that this study was based on visual measurements of distribution and behavior changes, mostly using human observations, and therefore has its limitations and biases. Moreover, it is based on a small sample size and highly variable data.

Interrelated Effects of Construction and Operations – Boating

The operation and use of over-water structures can also promote interrelated effects such as those originating from boating activities. In this regard, Warrington (1999a,b) reports on the increasing use of freshwaters in British Columbia for recreational boating. Warrington (1999a,b) divides the aquatic environment into bottom sediment, bulk water column, surface microlayer, and shoreline habitat compartments, within which the effects of recreational boating may occur. In each of these compartments, plant or animal tissue, non-living particulate matter, and water subcompartments may exist. A number of different kinds of effects may also occur and can be categorized as either physical disturbances or behavioral effects, which also include reproductive failure (Warrington 1999a).

With regard to physical disturbances, recreational boating can cause shoreline (i.e., bank) erosion, sediment resuspension, and destruction of shallow-water and marginal vegetation (see

Warrington 1999b for a discussion of chemical pollution associated with outboard motors). In several river systems it has been observed that the physical effects of boating traffic are more pronounced in narrow, shallow river channels than in deeper channels (Warrington 1999a).

In the Illinois River, the bed sediments (i.e., silts and clays) were easily resuspended. Small pleasure craft produced waves of less than a foot and caused the least amount of shoreline wave wash. Large pleasure craft produced short, steep waves of brief duration, causing bank erosion and turbidity increases. Towboats raised the water level at first, then water was drawn down, exposing the bottom, followed by successive waves rushing back in, with the resulting turbulence causing high turbidity. The turbidity trail extended several miles behind a towboat and took several hours to return to normal (Warrington 1999a).

Turbidity increases can be attributed in part to algal growth, which may result from the increased availability of nutrients (particularly phosphorus) originating from disturbed bottom sediments (Warrington 1999a). This condition occurs when propeller-induced mixing and resuspension of sediments makes phosphorus more bioavailable to phytoplankton, resulting in greater algal growth and thereby higher turbidities (Hilton and Phillips 1982; Yousef 1974 as cited by Warrington 1999a). In addition, a significant quantitative relationship has been observed between plant community structure, submerged plant abundance, and recreational boat traffic. In this regard, it is hypothesized that turbidity and its effect on light are the cause of a decreased abundance of submerged vegetation (Warrington 1999a). In addition to increasing nutrient availability, resuspension of sediments also incorporates metals and other toxic materials that may have been precipitated and thus previously removed from biological activity (Warrington 1999a).

Aquatic plants have variable susceptibility to being uprooted or eroded from the banks or from shallow water by wave action, and this is a function of both their root structure and the type of sediments in which they normally grow (see Warrington [1999a] for a list of British Columbia freshwater submerged aquatic plants ranked in order of their relative resistance to wave action). Uprooting of submerged aquatic vegetation was observed in the pathways of outboard engines where the propellers came within 30 centimeters of the substrate (Lagler et al. 1950).

Behavioral effects of boating operations are also a concern because amphibians, fishes, and other aquatic organisms can be affected. For example, noise produced by motorboats disturbs fishes and wildlife (Warrington 1999a). In this regard, it has been shown that boats traveling at slow speeds near sunfish nesting areas usually drive the males off the nest, thereby affecting their reproductive success (Mueller 1980; Lagler et al. 1950).

In general, water turbidity can have several deleterious effects on fishes (Warrington 1999a). Turbidity can cause decreased growth due to a reduction in the primary production (Buck 1959), promote mortality through gill damage, disrupt feeding behavior and migration (Noggle 1978), and decrease egg and fry survival (Campbell 1954; McNeil and Ahnell 1964, both as cited by Warrington 1999a).

A reduction in macroinvertebrate abundance due to boating operations has also been reported. Lagler et al. (1950) found that the invertebrate abundance in the path of an outboard motorboat operated over a prolonged period in shallow water was substantially reduced.

In the context of boating operations, interdependent effects of over-water structures can also be observed. For example, human activities such as wading and swimming that involve the intense use of the shallow, vegetated areas of lakes and streams can disturb feeding and nesting waterfowl (Warrington 1999a).

Construction activities have a concomitant and inevitable degree of water pollution. Petroleum products in minor quantities may seep into the water from construction equipment, and the exhaust emissions add hydrocarbons to the air (Mulvihill et al. 1980). In general, the resultant chemical processes potentially include water quality degradation due to 1) pollution originating from the structural material (i.e., treated wood); 2) temporary reduction of oxygen content associated with oxidation of resuspended organic matter during dredging operations; and 3) temporary changes in pH due to water contact with or leakage from concrete structures. Chmura and Ross (1978), Mulvihill et al. (1980), and Kahler et al. (2000) address all but the pH issue.

Physical/Chemical Environmental Disruption: Construction and Operations – Findings Summary and Data Gaps

Summary

Figure 4 schematically depicts the relationships among impacts resulting from changes induced by construction and operation of over-water structures and by pile removal activities. As illustrated in this figure, there may be temporary, permanent, and interrelated impacts. Temporary impacts are associated with noise disturbance and water turbidity, and consequently salmonid behavior disruption. Permanent impacts are related to bottom sediment disturbance, burial of benthic communities, nutrient load changes, and resulting alterations of habitat function. Interrelated effects such as those resulting from boating activity cause shoreline erosion and turbidity-induced light reduction, with the consequent elimination of aquatic vegetation. All of these processes could disrupt the food web and thus affect the ecosystem.

The following is a summary of findings of this literature review pertaining to disruptions induced by construction and operational activities.

- Physical/chemical environmental disruption due to construction and operation of over-water structures has both temporary and permanent effects on aquatic organisms, related to noise disturbance and water quality degradation.
- Physical processes include construction activities that disturb the bottom sediment, increase turbidity, adversely affect bottom-dwelling aquatic organisms, remove submerged aquatic vegetation, drive away fish and other mobile organisms, and alter existing habitat at the over-water structure site.
- Chemical processes include water quality degradation due to pollution, and temporary reduction of oxygen concentrations associated with oxidation of resuspended organic matter.
- Underwater impact-pile-driving noise is unlikely to significantly affect the migratory behavior of salmonids.

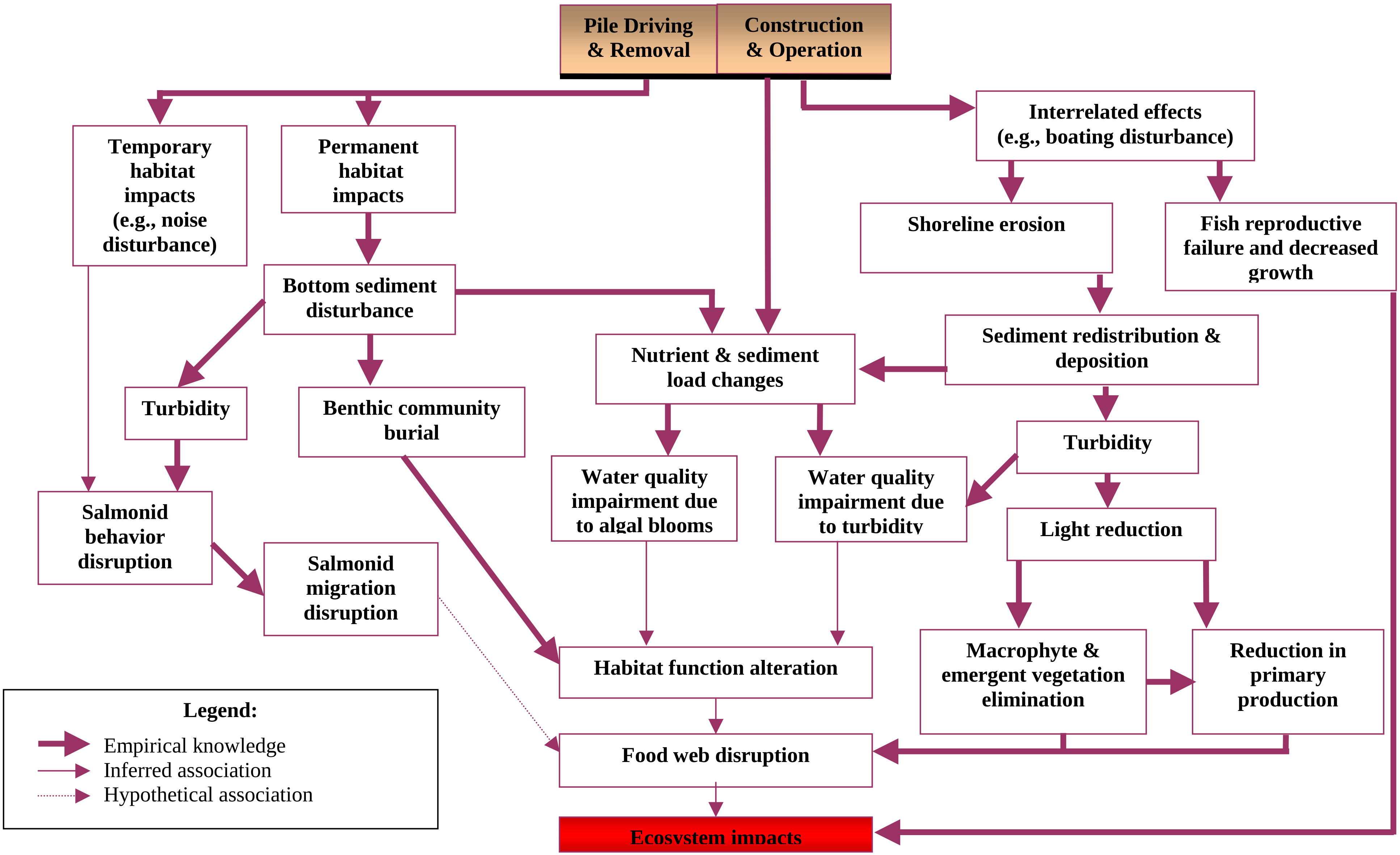

Figure 4. Impacts resulting from changes induced by pile driving and removal and other construction and operation activities.

- With regard to noise generated by pile driving, the threshold distance for an avoidance response has been experimentally determined to be approximately 10 feet.
- Infrasound generated by vibratory pile driving is not continuous, it has a short life span, and it is unlikely to have a significant impact on migrating salmonid behavior.
- Pile driving energy may affect salmonid eggs and embryos if they are located within 100 feet of the source.
- Operation of over-water structures can also have interrelated effects such as those caused by boating activities. These effects include physical disturbances and behavioral effects including reproductive failure.
- The interrelated physical effects include shoreline erosion, sediment resuspension (and resultant turbidity), and destruction of marginal aquatic vegetation and associated macroinvertebrate communities.
- Sediment resuspension creates turbidity that affects primary production, decreases bird fish-capture rate, damages fish gills,, decreases fish egg and fry survival, and can disrupt fish migration.
- Operational activities such as boating can have interdependent effects from the potential intense use of shallow, vegetated areas of lakes and streams by humans.

Data Gaps

No empirical data were found to support several of the processes depicted in Figure 4. Where empirical data are lacking, inferred and hypothetical associations have been drawn. The matrix of data availability in Appendix B shows where data exist under each of the categories of response addressed in this white paper (i.e., predation, behavior, and habitat function).

Through this literature review, the following information needs have been identified (organized by the observed type of response).

Predation

- Is there any relationship between physical/chemical environmental disruption and predator–prey interactions?

Behavior

- Would field studies corroborate or reject the experimentally determined threshold for fish response to impact pile driving (i.e., 10 feet)?
- Does avoidance response in fishes vary with the time of year, the system affected, or the species of fish?

- What are the effects of vibratory and impact pile driving on early stages (i.e., eggs and embryos) of aquatic organisms, particularly salmon?
- Does vibratory pile driving cause an avoidance response in juvenile salmonids at distances ranging beyond 20 to 30 feet from the pile driving activity? What would be the effect of this response on salmonid migration?
- What are the effects of boating on juvenile and adult salmonids? Can the reported effects on warm-water species be extrapolated to salmonids?
- Does turbidity disrupt migration of juvenile and adult salmonids?
- What are the effects of human activities such as wading and swimming, which involve the intense use of the shallow, vegetated areas of lakes and streams on aquatic organisms?

Habitat Function

- Does the energy from pile driving activities adversely affect salmonid eggs and embryos?
- Do 300 feet exclusion zones for pile driving activities provide adequate protection for eggs and embryos of salmonid species?

Habitat Protection, Restoration, and Mitigation Techniques

State of Knowledge

Shoreline development projects and interrelated activities can lead to habitat loss, which is one of the greatest threats to fisheries resources. Thomas (1994) considers the major causes of extinction of freshwater fishes in North America to be the loss or alteration of habitat (50 percent), the introduction of exotic species (37 percent), and over-exploitation of fisheries (8 percent).

Habitat alteration may lead to loss of habitat function and thereby to habitat loss. In recent years, several federal and state agencies, including U.S. Army Corps of Engineers, National Marine Fisheries Service, and Washington Department of Fish and Wildlife, have been implementing a policy of no-net-loss of certain critical habitats such as wetlands and eelgrass beds. Similarly, these agencies are implementing policies intended to prevent the introduction or spread of exotic species and the over-exploitation of fishery resources.

As outlined in Washington's *Statewide Strategy to Recover Salmon: Extinction Is Not an Option*, development projects occurring in or around water can replace damaged or lost habitat through the use of adequate and properly monitored mitigation techniques. Restoration of habitat in combination with strict controls to prevent exploitation of resources can contribute to the recovery of imperiled species. Strict controls to eliminate or minimize the access of exotic species can effectively restrict the continued spread of such organisms.

During the course of this review, literature was found addressing wetland protection, restoration, and mitigation, as well as stream bank protection and restoration. No documents were found specifically addressing lake and reservoir protection, restoration, or mitigation within the context of shore-zone development and construction of over-water structures. However, the information obtained regarding both wetlands and stream banks may be adapted for application to lakes and reservoirs, based on appropriate site-specific conditions and project-specific requirements.

For mitigation and restoration projects, the selection of adequate measures depends on project goals, objectives, and performance standards. There are clear criteria for mitigation projects: the habitat created and the functional value of the replacement habitat must be greater than values of the habitat replaced (Ecology 1998; Ecology et al. 1994). In contrast, for restoration projects, one must first ask to which historical condition a particular habitat must be restored. Unfortunately, this question does not always have a clear scientific answer and requires historical data that may not be readily available. Nonetheless, one can see that most of the general objectives of mitigation plans may apply to restoration projects.

Some of the objectives used in selecting wetland mitigation measures include the following (Ecology 1998; Ecology et al. 1994):

- The mitigation should be located in the same watershed and as close as possible to the affected area, and should provide the best possible contribution of functional values to the particular watershed system.

- Offsite mitigation efforts consolidated on one site are preferred to multiple offsite locations.

- Mitigation should provide better functional value than that provided by the wetland being replaced.

- Wetland mitigation in the form of wetland creation or enhancement must result in an overall net gain of wetland area over the wetland area being replaced.

- Mitigation sites must be of appropriate size and hydrologic condition in order to satisfy local, state, and federal requirements for wetland replacement (e.g., the wetland area lost must be replaced with a greater area of wetland created, and the functional value of the replacement wetland must be greater than the value of wetland replaced.

In addition, a monitoring plan should be implemented to evaluate the success of the created and enhanced wetland mitigation areas. For this purpose, quantifiable criteria included in the performance standards should be used as the basis for monitoring the success of the mitigation sites. Adequate mitigation techniques and timely implementation of best management practices (BMPs) can help to avoid, minimize, or compensate for impacts of proposed over-water structure projects. The basic goal of mitigation is to achieve no-net-loss of habitat functions by offsetting losses at the impact site (Washington 2000). These mitigation techniques must provide habitat protection and stability while achieving a range of parallel objectives, including terrestrial and aquatic habitat enhancement, water quality improvement, and ecosystem diversification (Schollen 1995).

Despite extensive expenditures under state and federal programs, there is little evidence in the literature to show that habitat restoration has actually improved the productive capacity of freshwater systems for salmonids. A reason for this is perhaps the lack of a clear understanding of the specific biophysical conditions that exemplify quality habitat. Although it is generally assumed that the use of BMPs has improved freshwater habitats (Independent Scientific Group 1996), empirical demonstration of the influences and benefits of BMPs on habitat is limited.

Therefore, designing to avoid environmental impacts should be a goal of all over-water structure projects. The structures should incorporate design elements that provide for fish habitat while preventing damage to the environment. However, when impacts cannot be avoided, mitigation techniques must be incorporated into the design and integrated into the operation of the structure. Thus, habitat restoration measures (either onsite or offsite, and either in-kind or out-of-kind) should be used to compensate for unavoidable habitat impacts. The site selection criteria for restoration activities should emphasize habitat connectivity, species occurrence and use, and ecological significance of the selected site from a holistic perspective (i.e., the ecosystem).

A crucial element to obtain a continued success of habitat protection and mitigation techniques is the inclusion of biological/environmental monitoring and evaluation of such techniques in programs and plans (Independent Scientific Group 1996). The importance of monitoring and evaluation is to ensure feedback to the state and federal agencies so that they can modify programs as needed to achieve their desired goals. In fact, effective observation and monitoring of the performance of mitigation plans is key to their success (Schollen 1995).

Monitoring data and general information from restoration sites can be used as the basis of watershed adaptative management plans, as well as to implement corrective actions in mitigated sites and to plan future restoration projects. For example, in a state listing of restoration projects, USEPA (2000) provides monitoring information ("lessons learned") from river corridor and wetland restoration projects. Among the elements contributing to the success of various projects, availability of monitoring information from other projects and follow-up to assure implementation and corrective actions when needed were among the most commonly cited attributes USEPA (2000).

This section of the white paper focuses on findings from the literature reviewed. Regulatory practices are described under the existing guidance summary section later in this paper. A few published sources provide information on habitat protection and mitigation techniques in the context of the over-water structures addressed in this white paper. Some of the information from early publications is outdated, and although it is discussed here, it should be used with caution. Mulvihill et al. (1980) provide regional considerations and information on function, site characteristics, environmental conditions, and placement constraints of over-water structures. Kahler et al. (2000) provide a series of conclusions and recommendations on effects of bulkheads, piers, and other artificial structures and shore-zone development on Endangered Species Act protected salmonids in lakes.

An important habitat mitigation tool is the use of bioengineering techniques. The draft *Integrated Streambank Protection Guidelines* (WDFW 2000) provides information on habitat impacts resulting from bank protection projects and describes several appropriate fish habitat mitigation measures, some involving bioengineering techniques. The guidelines are intended for streams, although some of the concepts and design criteria have applicability in lacustrine environments.

Similarly, *Streambank Revegetation and Protection: A Guide for Alaska* (ADFG 1996) provides information on bioengineering techniques developed to protect and restore stream banks. This guide also has applicability in lacustrine environments. In addition, *Soil Bioengineering, an Alternative for Roadside Management—A Practical Guide* (USDA-FS 2000) provides valuable techniques for stabilizing areas of soil instability, some of which are applicable to shorelines. However, soil bioengineering has unique requirements and therefore is not appropriate for all sites and situations (USDA-FS 2000).

Preservation and protection of shorelines and stream banks can be attained through a variety of approaches (USEPA 1993). However, based on the findings reviewed and presented in this white paper, preference should be given to nonstructural practices such as soil bioengineering, marsh creation, establishment and enforcement of no-wake zones, and establishment of setbacks.

Soil Bioengineering

Soil bioengineering refers to the installation of living plant material as a main structural component in controlling problems of land instability where erosion and sedimentation are occurring (USDA-FS 2000; USDA-SCS 1992). Native plants are used in order to ensure that the plant material will be well adapted to site conditions. Although a few selected species can be installed for immediate soil protection, it is expected that the natural invasion of a diverse plant community will stabilize the site through development of vegetative cover and a reinforcing root matrix (USDA-SCS 1992). Thus, adapted types of woody vegetation (i.e., shrubs and trees) are initially installed to offer immediate soil protection and reinforcement.

Soil bioengineering methods include an array of applied technologies that are effective not only for prevention but also for mitigation. These applied technologies combine mechanical, biological, and ecological principles to construct protective systems for the prevention of slope failure and erosion (USEPA 1993).

Soil bioengineering systems normally use rooted plants or cut, unrooted plant parts in the form of branches. As the systems establish themselves, resistance to sliding or shear displacement increases on shorelines, stream banks, and upland slopes. Examples of specific soil bioengineering practices include the following (USDA-FS 2000; USDA-SCS 1992):

- Native plant cutting and seed collection
- Salvaging and transplanting native plants
- Planting containerized and bare-root plants
- Distributing seed, fertilizer, and certified noxious weed-free straw or hay
- Live staking
- Installing erosion control blankets
- Installing live fascines
- Brush-layering
- Brush mattressing
- Branch-packing
- Live gully repair
- Installing vegetated geotextile
- Log terracing
- Joint planting
- Constructing live crib walls.

Information provided by USDA-FS (2000) and USDA-SCS (1992) on each of these techniques includes a description of required plant material, mechanism of action, advantages and disadvantages, tools needed, procedure for implementation, and applicability of the technique, as well as schematic cross-sections showing important design elements. While all of these techniques can be used for protection, restoration, and mitigation, they should be used on a project-specific and site-specific basis.

Marsh Creation

Another important technique that can be used to address shoreline erosion problems involves marsh creation and restoration. Plant marshes perform two functions in controlling shore erosion: dissipation of energy and stabilization of shoreline sediments. Energy dissipation is achieved through the exposed stems of plants (e.g., emergent vegetation), which form flexible masses that dissipate energy. Shoreline stability is achieved through dense stands of marsh vegetation, which create depositional areas that cause sediment accretion along the shoreline (USEPA 1993). Although most marsh creation techniques have been described for coastal areas (Knutson 1987, 1988; Lewis 1982), they also have great potential for application in freshwater environments (i.e., lakes, reservoirs, and sloughs).

Establishing and Enforcing No-Wake Zones

No-wake zones are useful tools for the prevention of shoreline and stream bank erosion and should be given preference over posted speed limits in shallow waters. The rationale is that, in theory, the boat speed that produces the maximum wake varies with the depth of the water (USEPA 1993). In shallow water, motorboats traveling even within speed limits produce wakes whose heights are equal to or near the maximum size that can be produced by the boats (USEPA 1993).

Establishing Setbacks

Another tool for the prevention of shoreline and stream bank erosion is the establishment of setbacks. Although a setback most often restricts the siting and construction of new structures along the shoreline, it can include requirements for the relocation of existing structures within the designated setback. In addition, setbacks can include restrictions on uses of waterfront and shore-zone areas that are not related to the construction of new structures (USEPA 1993). Finally, because setbacks effectively restrict the actual number of structures that can be placed on a given shoreline, they help to minimize the cumulative environmental effects of the structures.

Docks, Piers, and Floats

Because of increasing concern over the cumulative effect of over-water structures and, in response to the recent Endangered Species Act listing of several fish species, the Washington Department of Fish and Wildlife (WDFW) and the National Marine Fisheries Service (NMFS) are currently developing a series of documents establishing criteria for the construction of these structures. These documents provide recommendations and potential mitigation measures for implementation across the state. Many of these recommendations are not yet published and are available only through WDFW area habitat biologists and NMFS staff. Although not all the recommendations are yet supported by published scientific research (i.e., empirical data), these recommendations are intended to lessen or mitigate potential cumulative effects, as well as to protect fishes. Some of the documents containing criteria and mitigation measures currently recommended by WDFW (undated[a,b,c,d]) and the NMFS (2000) for eastern Washington are presented below.

- *WDFW Salmonid Predation Reduction Measures and Dock Specifications for North Central Washington Water Inhabited by Federally Listed Fish Species* (WDFW undated[a]). This document includes some typical WDFW salmonid predation reduction requirements for dock-associated structures, specifically for piers, floats, ramps, piling, and anchors. These requirement include regulation of the following elements: 1) pier size and shape; 2) ambient light grid requirements; 3) piling size, number, and surface characteristics; 4) minimum distance waterward of the ordinary high water mark; 5) characteristics of anchors when used in lieu of pilings.

- *Some Typical WDFW Salmonid Predation Reduction Measures and/or HPA Dock Requirements on North Central Washington Waters Inhabited by Listed Fish Species Protected Under the Federal Endangered Species Act*. (WDFW undated[b]). This document includes criteria addressing the structure dimensions, avoidance of both light penetration reduction and creation of shaded areas, avoidance of predatory fish habitat creation, damage avoidance of near-shore shallow water habitats, and minimization of pile usage. The document includes the following eight criteria: 1) dock and float size and shape; 2) ambient light grid requirement; 3) minimum open water zone and distance from shoreline for floats; 4) ramp grating for light penetration and minimum ramp length; 5) dock and float anchoring; 6) piling surface characteristics; 7) reflective surface finish on flotation devices; and 8) minimum vertical distance between the ramp and float and the stream or lake bed.

- *Recommendations for Siting Marinas and Other Overwater Structures in the Lower Columbia River* (WDFW undated[c]). This document is intended to provide recommendations and mitigation measures necessary to achieve no-net-loss of productive capacity of fish and shellfish habitat. The document includes three levels of mitigation: avoidance of impacts, minimization of impacts, and compensation for impacts. Under avoidance of impacts, the following criteria are included: 1) dock and float size and shape; 2) minimum distance waterward of the ordinary high water mark; 3) maximum number of piling landward of Columbia River datum; 4) float characteristics and location; 5) treated piling restriction; 6) over-water structure siting in relation to water depth; 7) characteristics of breakwaters; and 8) preservation of a buffer along the shoreline. Under minimization of impacts, the following criteria are included: 1) size, number, siting location, and ambient light grid requirement of over-water structures; 2) bioengineering approach to shoreline protection; 3) location for boat mooring; and 4) dredging requirements. Under the compensation for impact section, the following criteria are included: 1) restoration of filled, armored, or otherwise modified shorelines; and 2) restoration of salmonid habitat covered by over-water structures.

- *Conditions for Siting of Marinas and Boat Docks in Water Containing Anadromous Fish* (WDFW undated[d]). This document includes conditions and measures to minimize or avoid adverse effects of a proposed action on listed species and minimize or avoid adverse modification of critical habitat in freshwater. The document is intended for eastern Washington and has an appendix that includes approved in-water work windows for that region.

With regard to the recommended use of bright white PVC and paint and reflective metals for the construction of docks and associated structures referred to in the second bullet point above, empirical data obtained from the literature survey for this paper show that prey and predator fishes are attracted to white-painted floats to the same degree that they are attracted to non-white or reflective materials (Helfman 1979). Anecdotal evidence from sport fisherman and recreational scuba divers supports such empirical data. Therefore, this recommendation bears further research.

The NMFS is preparing an incidental *take statement* document, which contains "reasonable and prudent measures" necessary to minimize the take of Endangered Species Act listed and proposed species (NMFS 2000). The document addresses the upper Columbia River steelhead and spring chinook populations. The basis of this incidental take statement is that over-water structures provide an incremental enhancement to predator habitat that is directly related to the surface area of the over-water structure (NMFS 2000).

Criteria and mitigation measures specific to the construction of over-water structures in western Washington are also being developed by the NMFS. In addition, guidelines for the biological assessment of such structures have recently become available for use by project proponents. The NMFS (2000) criteria outlined below were adapted from *Guidance for ESA Section 7 Consultation—Effect Determinations for New and Replacement Piers and Bulkheads in Lake Washington* (NMFS 2000).

The safest months for construction, considering all life stages of the chinook, are November and December. In non-delta areas, August, September, and October should be construction windows with appropriate sedimentation controls. Projects that may qualify as "not likely to adversely affect" are those that fall under the following criteria:

- Replacement pier on existing footprint with materials that do not further degrade baseline conditions
- Replacement pier area and number and diameter of pilings significantly reduced
- New minimum-sized pier with narrow, elevated walkway and minimal number and diameter of pilings, providing for a shallow near-shore

migration and feeding zone, and including aquatic and riparian vegetation rehabilitation

- Shoreline rehabilitation directed toward providing complex in-water habitat (e.g., emergent plants; some woody debris with branches) and riparian vegetation with mixture of native trees, shrubs, vegetation overhanging the water, and ground covers.

Within the context of habitat protection and mitigation, both direct and indirect modifications of structural complexity of the aquatic environment have been used to protect and improve habitat. Direct or indirect manipulation of aquatic vegetation alters a wide variety of variables simultaneously (Cooper and Crowder 1979). For example, manipulation of brush shelter, rock rubble, and other artificial stream and lake improvement technologies can directly alter substrate areas, light penetration, and prey refuges. These same manipulations can also indirectly alter nutrient cycles, water chemistry, and food resources (Cooper and Crowder 1979).

The effects of docks, piers, and wharves can be minimized if these structures are constructed high enough above marshes to allow light to reach the water surface (Chmura and Ross 1978). In this regard, light-penetrating elevated walkways can be used for preventing stream bank damage where access to a sensitive or critical area is required (ADFG 1996). These structures prevent erosion and protect underlying vegetation, allowing vegetation recovery while providing access. Floating docks can be connected to elevated walkways to provide boating access (ADFG 1996). In addition, it is recommended that docks and piers extend out far enough to reach depths in which dredging will not be required (Chmura and Ross 1978). In a literature review of the effect of marinas, Chmura and Ross (1978) found that floating docks and pile-supported piers have the least effect on water circulation and therefore are preferred to solid structures. It should be pointed out, however, that Chmura and Ross' (1978) recommendation on floating docks does not take into consideration the shade avoidance criteria set forth by the revised WAC 220-110-60, which requires maximum height to minimize shading of the area under the structure.

Chmura and Ross (1978) also recommend avoiding painting underwater surfaces. The basis for this recommendation is that over-water structures such as docks and piers "provide additional substrate for the growth of fouling communities." Painting of the wood surfaces discourages such growth. Other researchers (Mulvihill et al. 1980) recommend that if structures are painted or otherwise covered, all coatings must be dry before placing floats in the water to avoid contamination.

Marinas

Mulvihill et al. (1980) provides a review of biological impacts of minor shoreline structures, but mostly in marine environments (see Mulvihill et al.1980 for study review and recommendations beyond the scope of this white paper). Site selection and corresponding site-specific engineering design are the first steps in environmental impact avoidance. For example, a site with maximum natural protection will minimize alterations and the concomitant adverse impacts of construction of marinas (Mulvihill et al. 1980).

In general, attention to selection of sites with the "maximum natural physical benefits" can help to avoid alterations and continual maintenance associated with dredging (Mulvihill et al. 1980). To minimize impacts, it is recommended that marinas be located "…at the end of, or between drift sectors, or on self-contained pocket beaches…" (Bauer 1973 as cited by Mulvihill et al. 1980).

Warrington (2000) provides comprehensive recommendations for best management practices (BMPs) to be employed during the construction and operation of marinas. The recommended BMPs are grouped by activities, including choice of location; construction; management of liquid waste, fuel, and solvents; sewage disposal; boat cleaning; boat coating; generation and disposal of solid waste; and protection of upland areas. However, these BMPs, which are proposed for construction activities in British Columbia, Canada, may not all apply in the state of Washington because of differences in laws and regulations, or they may not provide a sufficient level of environmental protection.

Quoted below are selected recommendations proposed by Warrington (2000) that apply to marinas in freshwater environments. These recommendations are in essence BMPs that should be incorporated as permit conditions for individual projects, in order to ensure that these BMPs are implemented (Fresh 2000 personal communication):

Choice of Location

- *Avoiding construction of mooring basins in blind channels or sloughs where there is insufficient tidal current or natural flow to ensure adequate and regular flushing*
- *Providing two entrances to provide for maximum flushing action*
- *Orienting the basin entrance to provide for maximum tidal flushing and prevailing current water exchange*
- *Orienting marina floats with currents or prevailing winds to prevent trapping surface debris and oily residue*
- *Designing marinas to retain as much existing natural aquatic and marginal vegetation as possible*

Construction

- *Constructing dredged basins with more than one water depth; the depth must decrease with distance from the entrance; to avoid internal deeper pockets which act as un-flushed holding basins*
- *Timing construction and dredging to periods when use of the site by fish is minimal*

- *Using floating or pile breakwaters rather than rubble mounds to minimize site impacts*
- *Using bubble curtains or padding to disrupt the shock wave when blasting*
- *Cutting boat or float plane ramps out of the upland rather than building them on intertidal foreshore*
- *Constructing gradual slopes which can be stabilized by natural vegetation rather than rip rap or walls*

Liquid Waste, Fuel, and Solvent Management

- *Providing fueling equipment with automatic shut-off nozzles to reduce spillage during fueling operations*
- *Providing impervious pavement, berms, curbs or other means of spill containment, spill control equipment and connection to spill collection sumps for fuel and storage tank areas*
- *Avoiding the use of underground storage tanks which lead to very expensive clean up costs when they eventually corrode and leak and cause extensive ground and water pollution*
- *Storing fuels and other highly inflammable fluids in a separate area to meet local fire department regulations*
- *Providing fluid storage containers with level indicators to prevent overfilling and spillage*
- *Keeping an accurate and up-to-date inventory of everything in storage for use by spill cleanup crews and fire fighters so that potentially hazardous combinations can be anticipated*
- *Avoiding discharge of on-site oil/water separator waste water to sewers or to ground unless it is demonstrated to contain less than 15 mg/L of oil*
- *Preventing discharge of any waste liquids down floor, sink or storm drains; signing all drains*
- *Establishing site-specific spill contingency plans, including reporting, and training employees in use of the required equipment*

Sewage Disposal

- *Providing fixed point pump-out facilities consisting of one or more centrally located sewage pump-out stations, generally situated at the end of a pier and often on a fueling pier for convenience; pumps or a vacuum system with flexible hose attachment draw wastewater from a docked plane's or boat's pump-out fitting and move it to an onshore holding tank, a pubic sewer system, a private treatment facility, or another approved disposal facility; for boats with small, removable toilets, a similarly connected dump station should be provided*

- *Providing portable pump-out facilities which function the same as the fixed-point system with the advantage of mobility for servicing different docks; wastes are drawn from a docked boat's pump-out fitting via vacuum or pump setup and hose attachment into a storage tank; the full tank is discharged into the marina's disposal facilities; these are thought by many to be the most economical and logistically feasible means of ensuring proper disposal of boat sewage*

- *Providing continuous wastewater collection at the slip where live-aboard vessels are situated, this would involve fixed force main piping, pumping, and sewage disposal means on the part of the marina; language should be included in slip leasing agreements mandating the use of pump-out facilities and specifying penalties for failure to comply*

- *Discharging sanitary wastes, black water and grey-water, to the municipal sewer, having it trucked/shipped out or pumped to a septic system or shore*

Boat Cleaning

- *Removing boats from the water to perform cleaning where feasible*

- *Cleaning boats in the water by hand*

- *Using detergents and cleaning compounds that are phosphate-free and biodegradable*

- *Avoiding use of detergents containing ammonia, sodium hypochlorite, chlorinated solvents, petroleum distillates, or lye*

- *Collecting hull wash water and removing solids before discharge to sewers or ambient waters*

- *Cleaning dock floors, lift platforms and yard surfaces before high pressure washing hulls*

- *Avoiding pressure washing on tidal grids, docks, planked and grated surfaces or other areas where the wash water can not be contained*

- *Pumping collected wastewater which contains low concentrations of pollutants directly into the sanitary sewer*

- *Treating small volumes of wastewater volume with high pollutant concentration directly by a mechanical filter system with the filtrate going to the sewer system and the sludge to an approved disposal facility*

- *Monitoring the quality of the water discharged to sewers or ambient waters*

- *Avoiding pressure washing on tidal grids or when beached unless there is a collection system and sump to collect all wash water; cleaning out the sump before tidal flooding; sump contents may be special waste*

- *Covering or installing filters on floor drains to prevent entry of spent grit into sumps and sewers*

- *Avoiding discharge of dry-dock flood water, cooling water, condenser water, boiler blow-down water and steam cleaning water to ambient waters if oil and grease exceeds 10 mg/L, turbidity exceeds 5 NTU over background or pH is outside the range 6.0 to 8.0*

Boat Coating (Painting and Anti-Fouling)

- *Avoiding spraying coatings while a vessel is on a tide grid or beached*

- *Using soft anti-fouling paint where cleaning is infrequent and hard paint where cleaning is needed frequently*

- *Applying anti-fouling coatings well away from sensitive fish habitat, shellfish beds, fish farms, shallow estuarine areas and surface storm drains*

- *Using tarps while vessel is on a tide grid, beached or on planked or grated docks and removing the tarps before the grid floods, it rains or washing occurs*

- *Using airless or high volume low pressure spray guns and monitoring wind drift*

- *Using brushes or rollers when vessel is afloat except when tops are fully shrouded*

- *Permitting use of tributyl tin paints only by licensed operators*
- *Avoiding use of tributyl tin paints on non-aluminum hulls under 25 m long*
- *Avoiding painting under high wind conditions when drift is evident*

Solid Waste Generation and Disposal

- *Ensuring that solid waste from boat operation and maintenance at marinas is properly disposed of or recycled regularly*
- *Prohibiting in-the-water hull scraping or any process for removing paint from the boat hull that occurs underwater*
- *Providing proper waste disposal facilities including recycling facilities where possible*
- *Providing filters on all drains to keep debris from entering stormwater or sewers*
- *Providing sufficient area above the high water line, for boat repair and maintenance; such work should not be allowed outside of designated areas*

Protection of Upland Areas

- *Providing a paved upland area for cleaning and painting*
- *Providing proper waste disposal facilities including recycling facilities where possible*
- *Collecting all surface runoff from paved upland areas in a storm water collection system*
- *Passing all the collected storm water through a sediment and oil separation treatment prior to discharge*
- *Collecting all paint and cleaning residues and storing in a covered container prior to off-site disposal*
- *Collecting all oil and filters for recycling or off-site disposal*
- *Using submerged outfalls which extend beyond tidal or seasonal low water levels*

Riprap and Retaining Walls

As with any structure, the design and material choice for the construction of bulkheads can be altered to minimize their impact. Nonetheless, regardless of the design, these structures will modify the environment and thereby adversely affect aquatic organisms, in a cumulative fashion.

The NMFS (2000) has recently released a document with guidelines for the determination of effect of piers and bulkheads that may be constructed or replaced in Lake Washington. In the context of bulkheads, the NMFS has proposed as "not likely to adversely affect" those projects that fall under the following criteria:

- Replacement bulkhead on existing footprint with materials that do not further degrade baseline conditions.
- Replacement bulkhead footprint set back from the ordinary high water mark, with shoreline rehabilitation including overhanging vegetation.
- Replacing bulkheads with bioengineered bank protection and significant shoreline vegetation rehabilitation including overhanging native plants.

In general, when planning armoring structures (i.e., bulkheads), the total effect of the structure on the environment should be considered (Mulvihill et al. 1980). In their review, Mulvihill et al. (1980) present biological considerations for the construction of bulkheads. Although most of these considerations were obtained from studies conducted in marine and estuarine environments, the general principles of habitat conservation should apply to projects in the freshwater environment. Some of the recommendations include using designs that minimize damage to fish and shellfish habitat, avoiding the disturbance of shoreline vegetation, enhancing existing vegetation to provide shoreline stabilization, setting bulkheads landward of the mean high waterline, and restricting amounts of suspended sediments during construction (Mulvihill et al. 1980).

Bonham (1983) field-tested whether emergent vegetation could attenuate wave energy in large canals and rivers in Britain (see Bonham 1983 for details of the bioengineering design). The emergent vegetation (four species tested) was capable of dissipating approximately two-thirds of boat wake energy and inhibiting wave break. Based on his results, Bonham (1983) proposed the use of emergent vegetation for shoreline wave-energy attenuation and scour prevention.

Once anthropogenic processes are initiated, and physical responses such as erosion-induced habitat alteration are observed, corrective measures may have profound repercussions on the ecosystem and therefore should be used with caution. For example, Rolletschek and Kuhl (1997) investigated the impacts of reed-protecting structures on shorelines in the lower Havel River and Great Müggel Lake, Berlin. The purpose was to address an existing cycle of reed destruction due to erosion. Faggots and palisades successfully protected reeds by acting as wave breakers and reducing erosion in the reedy areas of the shoreline. However, depending on the type of reed-protecting structure used (i.e., gester faggots, reisig faggots, or palisades), increased sedimentation, increased nutrient concentration, and enrichment in fine sulfide-containing detritus occurred, with a corresponding decrease in water quality.

Pile Driving and Removal

No literature on mitigation techniques for pile driving and removal in freshwater was found. However, one recent study conducted in a marine environment addresses the use of bubble curtains to minimize the impact of noise produced during underwater construction (Würsig et al. 2000).

Würsig et al. (2000) conducted experiments near Hong Kong on the use of bubble curtains to minimize the impacts on Indo-Pacific hump-backed dolphins from noise produced during underwater construction. Percussive pile-driving techniques were used from a barge, and a bubble curtain was used as a mitigation measure to protect wildlife, in particular the hump-backed dolphins. These researchers found that when barges were not in the sound-propagation path, the bubble curtain provided a reduction of 3 to 5 decibels in the overall broadband sound level. Conversely, when the barge was in the sound propagation path measured by the receiver systems, bubble screening was much less effective. This was probably due to the vibrations of the barge with every percussive blow, which transmitted the piling noise over the curtain. Bubble screening of entire sound-emitting structures could reduce sound even more.

Some dolphins stayed in the vicinity during construction activities, but many appeared to temporarily abandon the construction area (possibly due to other factors). However, dolphins were observed during construction or pile driving periods traveling at speeds over twice those observed during non-pile-driving periods. It is not certain whether increased speeds were a result of increased stress related to construction (Würsig et al. 2000).

Construction and Operational Activities

With regard to construction-specific activities aimed at protection and mitigation during the construction of over-water structures, only a few published reports were located. One of those reports is the literature review prepared by Mulvihill et al. (1980), which provides general construction recommendations. Two of the relevant recommendations are presented below.

- The placement of the structure relative to the sun, as well as the height and width of the deck of over-water structures, are important factors to consider. The structure should be placed high enough above the water to prevent shading. A narrow pier extending from north to south will not produce as much shade as a wide pier running from east to west (Mulvihill et al. 1980).

- The size, number, and placement of pilings should be evaluated in relation to the various biological zones over which the pier will extend.

Warrington (1999a) compiled and reported data concerning best management practices for construction, specific to surface stabilization. Quoted below are selected recommendations presented in the report that apply to activities associated with the construction of over-water structures. As stated previously, these recommendations are in essence BMPs that should be incorporated as permit conditions for individual projects, in order to ensure that these BMPs are implemented (Fresh 2000 personal communication):

Scheduling

- *Coordinating the timing of land disturbing activities and installation of erosion and sedimentation control measures to minimize water quality impacts*
- *Scheduling (in-water) construction to avoid the period when either fall or spring spawning fish or their eggs and larvae are present*
- *Designing and planning the development of roads, utilities, and building sites with as little excavation and disturbance as possible*
- *Planning construction activities during the dry season to minimize erosion*
- *Staging development so that parts are being re-vegetated and parts have not been stripped yet to minimize the proportion which is actively bared and easily eroded*

Surface Protection

- *Carrying out watering, mulching, sprigging, or applying geotextile materials to a construction area to prevent soil loss as dust*
- *Mulching, a protective blanket of straw or other plant residue, gravel or synthetic material applied to the soil surface, to minimize raindrop impact energy and runoff, foster vegetative establishment, reduce evaporation, insulate the soil and suppress weed growth*
- *Seeding (permanent) to establish a perennial vegetative cover to minimize runoff, erosion and sediment yield on disturbed areas; disturbed soils typically require amendment with lime, fertilizer and roughening; seeding should be done together with mulching; mixtures are typically most effective and species vary with preferences, site conditions, climate and season*
- *Sodding to give permanent stabilization of exposed areas by laying a continuous cover of grass sod*
- *Seeding (temporary), planting rapid-growing annual grasses, small grains or legumes, to provide initial, temporary stabilization for erosion control on disturbed soils that will not be brought to final grade for more than approximately one month; seeding is facilitated by fertilizing and surface*

roughening; broadcast seeds must be covered by raking or chain dragging, while hydro-seed mixtures are spread in a mulch matrix

- *Treating disturbed soil with polyacrylamide (PAM) to increase infiltration and reduce suspension of soil particles*
- *Top-soiling, preserving and subsequently re-using the upper, biologically active layer of soil, to enhance final site stabilization with vegetation*

Runoff Control

- *Grading surfaces to redirect sheet flow*
- *Using diversion dikes or berms force sheet flow around a protected area*
- *Covering temporary stockpiles and backfill materials to prevent erosion and sedimentation*
- *Using silt fences to contain runoff from easily eroded slopes*

Sediment Traps

- *Constructing sediment traps, small, temporary ponding basins formed by an embankment or excavation to capture sediment from runoff; traps are most commonly used at the outlets of diversions, channels, slope drains or other runoff conveyances that discharge sediment-laden water; it is important to consider provisions to protect the embankment from failure from runoff events that exceed the design capacity; plan for non-erosive emergency bypass areas; make traps readily accessible for periodic maintenance; high length-to-width ratios minimize the potential for short-circuiting; the pond outlet should be a stone section designed as the low point*
- *Constructing sod drop inlet protection which consists of a permanent grass sod sediment filter area around a storm drain drop inlet for use once the contributing area soils are stabilized; this is well-suited for lawns adjacent to large buildings*
- *Constructing vegetated filter strips (VFSs) as a low-gradient vegetated area that filters solids from overland sheet flow; they can be natural or planted, should have relatively flat slopes, and should be vegetated with dense-culmed, herbaceous, erosion-resistant plant species; the main factors influencing removal efficiency are the vegetation type and condition, soil infiltration rate and flow depth and travel time, which are affected by size of contributing area, and slope and length of strip; channelized flows decrease their effectiveness; they are often used as buffers bordering on construction areas; level spreaders are often used to distribute runoff evenly across the strip*

The operation and use of over-water structures also cause interrelated effects associated with boating activities. Warrington (1999a) compiled and reported data concerning the impact of recreational boating in freshwater environments (see also Warrington 1999b for water pollution associated with boating activities). Quoted below are a summary of selected recommendations presented in the report:

- *To minimize bottom erosion, sediment suspension, vegetation loss and effects on wildlife, normal use of motorized boats should be restricted to water depths where the propeller or jet drive is at least 2 and preferably 3 meters above the sediment or vegetation surface, except at carefully selected boat launch sites. Also, in narrow channels (up to 3 boat lengths wide) boat speeds should be restricted to 'no wake.'*

- *Heavy planting of floating and emergent native vegetation will help to protect the shoreline from wave-caused erosion.*

- *A minimal number of specified access channels between shallow and deeper water should be marked and used exclusively. These should be as short and direct as possible and should have wake limits imposed.*

- *Boats should not be permitted to operate in an area where they would be considered confined (boat cross-sectional area exceeds 5% of the cross-sectional area of the waterway). This is necessary to prevent bank erosion, sediment resuspension and destruction of marginal and shallow water vegetation.*

- *To preserve viable waterfowl and fish populations, all boating, fishing and other human activities need to be excluded from breeding and overwintering habitats during the critical seasons.*

Habitat Protection, Restoration, and Mitigation Techniques—Data Gaps

A number of data gaps were identified during the review of literature pertaining to habitat protection and mitigation techniques for the construction of over-water structures. Further research to answer the following questions would serve to fill these data gaps.

- Which mitigation techniques are most effective in minimizing the loss of habitat or ecological function?

- Are the project goals, objectives, and performance standards used for wetland mitigation applicable to lakes and reservoirs?

- For restoration projects, how should project goals, objectives, and performance standards define targeted 'historical conditions'?)

- What is the best means of preventing erosive cycles that preclude the recovery and reestablishment of emergent vegetation?

- Does the use of bright white PVC and paint or reflective metals for the construction of in-water structures tend to prevent or decrease predator fish use of the structures?

- Which design features of docks and piers are most effective in preventing or minimizing the environmental effects of these structures? Which features are most effective in minimizing their cumulative effects?

Summary of Existing Guidance

Regulatory Framework Governing Over-Water Structures in Freshwater

The regulatory framework governing construction and maintenance of over-water structures consists of federal, state, and local laws and administrative rules and guidelines. Following is a description of each of the applicable laws, codes, regulations, and other documents that make up the current regulatory framework.

Federal Laws and Regulations

National Environmental Policy Act (NEPA) *(42 United States Code [USC] 4321 et seq.)*

Federal agencies making funding decisions or issuing permits for over-water structures are required to comply with the National Environmental Policy Act. If the impacts of the over-water structure are determined to be environmentally significant, an environmental impact statement (EIS) is required. If the NEPA lead agency determines that the over-water structure will not significantly impact the environment, that agency issues a *finding of no significant impact* (FONSI).

Clean Water Act Section 404 *(33 USC 1344 et seq.; USC 1251 et seq.)*

Construction of over-water structures that would result in discharge or excavation of dredged or fill material in United States waters, including wetlands, requires a Clean Water Act section 404 permit issued by the U.S. Army Corps of Engineers and/or the U.S. Environmental Protection Agency. The U.S. Fish and Wildlife Service, National Marine Fisheries Service, and Washington Department of Fish and Wildlife also play significant roles in the implementation of the section 404 permitting process (as authorized by the Fish and Wildlife Coordination Act).

River and Harbors Act Section 10 *(USC 403 et seq.)*

Any work affecting navigable waters of the United States that extends to the ordinary high water mark in freshwater areas (including the construction of piers, docks, and floats) requires a section 10 permit issued by the U.S. Army Corps of Engineers. Navigable waters as defined in the River and Harbors Act include all presently, historically, and reasonably potential navigable waters, and all waters subject to the ebb and flow of the tide, up to mean higher high water in tidal waters and up to ordinary high water in freshwater areas.

Endangered Species Act *(16 USC 1531 et seq.)*

Because of the recent listing of several anadromous fish species for protection under the Endangered Species Act, and because many of the freshwaters of the state of Washington provide habitat for those protected species, construction of over-water structures and shoreline development in general must comply with the requirements of the statute. The Endangered Species Act provides broad protection for fish, wildlife, and plant species that are listed as threatened or endangered. Provisions are made for listing species and designating critical habitat for listed species, as well as for recovery plans. The statute outlines procedures for federal agencies to follow when taking actions that may jeopardize listed species, and contains exceptions and exemptions. The shoreline development activities that have federal nexus (i.e., federal funds or federal permits) are subject to review under the statute. Among these activities, construction, replacement, or repair of piers, docks, mooring buoys, boat canopies, boathouses, pilings, and bulkheads require a U.S. Army Corps of Engineers permit and thereby are subject to review under the Endangered Species Act.

State Laws and Regulations

State Environmental Policy Act (SEPA) *(Revised Code of Washington [RCW] 43.21C)*

An over-water project proposal that requires a state or local agency permit is first required to undergo a SEPA review. In accordance with SEPA rules, one agency is identified as the lead agency for this review. This agency may determine that a project proposal is categorically exempt, or is clearly in compliance with the provisions of SEPA, in which case the SEPA review process is satisfied. If further clarification is needed, the lead agency can ask an applicant to fill out an environmental checklist, answering a standard series of questions to determine whether the project would have a significant adverse impact on the environment. If it is determined not to pose this threat, then the proposal is granted a *determination of nonsignificance* (DNS) and is considered to be in compliance with SEPA. If the proposed project is considered to pose significant adverse impacts to the environment, then an environmental impact statement (EIS) must be drafted, publicly reviewed, and finalized.

Shoreline Management Act (SMA) *(RCW 90.58)*

Construction of any type (including over-water structures) in waters of the state or in the adjacent regulated shoreline area, if it is valued at $2,500 or more ($10,000 if the project is a pier), requires a shoreline management substantial development permit issued by the city or county and reviewed by the Washington Department of Ecology. Shorelines in freshwater areas include all lake and reservoirs greater than 20 acres and their associated wetlands, and all streams and river segments with a mean annual flow greater than 20 cubic feet per second and their associated wetlands. The shoreline designation extends horizontally 200 feet from the ordinary high water mark.

Other activities in the water or shoreline area may require conditional use permits or variances also issued by the Department of Ecology. All permit activities are subject to appeal by citizens, applicants, and government agencies. Appeals are heard by the Shoreline Hearings Board.

The Shoreline Management Act requires local governments to write *shoreline master programs* that regulate streams, lakes over 20 acres, and marine waterfronts. There are 247 city and county master programs currently in effect that were written based on state guidelines. These guidelines are being revised (WAC 173-16). Cities and counties regulate projects in or adjacent to state waters with their comprehensive plans, shoreline master programs, and other development regulations. The local laws and regulations that affect development activities (more specifically on- and over-water structures) in waters of the state vary from one jurisdiction to another, but include critical area development regulations (adopted under the state Growth Management Act) and environmental designations under shoreline master programs (adopted under the state Shoreline Management Act).

Clean Water Act Section 401 *(33 USC 1251 et seq.)* *and Coastal Zone Management Act* *(16 USC 601 et seq.)*

These federal laws are administered by the Washington Department of Ecology. Application for a federal permit under section 404 of the Clean Water Act to discharge dredge or fill material into state waters or wetlands, or to excavate in water or wetlands, triggers review under these laws. Section 401 certification and coastal zone consistency certification are issued by the Washington Department of Ecology.

National Pollutant Discharge Elimination System (NPDES)

The federal NPDES program is administered in Washington by the Department of Ecology. If a project disturbs more than 5 acres at one time, an construction permit must be issued by the Department of Ecology to ensure that state and federal water pollution provisions are upheld.

Hydraulic Project Approval Code *(RCW 75.20 and Washington Administrative Code [WAC] 220-110)*

Construction or operation of an over-water structure that would use, divert, obstruct, or change the natural flow or bed of any freshwater or saltwater of the state requires a hydraulic project approval issued by the Washington Department of Fish and Wildlife.

The Washington Administrative Code **(**WAC 220-110-060) regulates the construction of freshwater docks, piers, and floats and the driving and removal of pilings. As a result of the recent listing of fish species under the federal Endangered Species Act, state regulations are currently being revised to include all in-, on-, and over-water structures, and to grant a greater level of protection to endangered species and the environment, based on the best scientific data available. Similarly, WAC 220-110-224, which regulates freshwater boat hoists, ramps, and launches, is being revised to address the issue of cumulative effects of the siting of these structures, and to provide more specific regulatory language regarding the uses of these structures within the context of habitat and species protection.

In addition, under the state hydraulic code, WAC 220-110-223 regulates the construction of bulkheads, and WAC 220-110-050 addresses bank protection.

A memorandum of agreement between the Washington Department of Fish and Wildlife, the National Marine Fisheries Service, and the U.S. Fish and Wildlife Service was signed on April 4, 2000 to develop an Endangered Species Act compliance agreement for hydraulic project approvals, which are issued by the Department of Fish and Wildlife under RCW 75.20. This memorandum of agreement provides language that addresses freshwater projects, including in-, on-, and over-water structures (section 5.C(3)(f)), oversight and monitoring (section 7), and adaptive management (section 10).

Forest Practices Act *(RCW 76.09)*

Any timber harvest or roadwork in a riparian management zone or riparian area associated with construction of an over-water structure requires a forest practices permit issued by the Washington Department of Natural Resources. This permit may require that forest landowners undertake corrective and remedial actions to reduce the impact of any forest practice that may be associated with a proposed project. The goal is to afford protection to forest soils, fisheries, wildlife, water quantity and quality, air quality, recreation, and scenic beauty.

Aquatic Lands Act *(RCW 79.90)*

Use of state-owned aquatic lands, including tidelands, shorelands, and beds of navigable waters, requires an aquatic use authorization (aquatic lease) issued by the Washington Department of Natural Resources.

Water Pollution Control Act *(RCW 90.48)*

A temporary exceedance of state water quality standards established by WAC 173-201A for in-water work (e.g., change in pH or turbidity) requires a Washington water quality standards modification issued by the Washington Department of Ecology.

Aquatic Resource Mitigation Act *(RCW 90.74)*

This law establishes a state policy to authorize innovative mitigation measures, by requiring state regulatory agencies to consider mitigation proposals for infrastructure projects that are timed, designed, and located in a manner to provide equal or better biological functions and values compared to traditional onsite, in-kind mitigation proposals. When making a regulatory decision, the agencies must consider whether the mitigation plan provides equal or better biological functions, compared to the existing conditions, for the target resources or species. The factors that agencies must consider in making this decision are identified in the state hydraulic code, the state Water Pollution Act, and the Aquatic Resource Mitigation Act.

Salmon Recovery Act *(RCW 75.46/ESHB 2496)*

In 1998 the Washington State Legislature passed the Salmon Recovery Act, in response to the state’s need for a coordinated approach to respond to the listing of salmon and steelhead runs as threatened or endangered under the federal Endangered Species Act.

Wetland Mitigation Banking *(RCW 90.84)*

In 1998 the Washington State Legislature passed legislation establishing wetland mitigation banking as one element of compensatory mitigation. The law directs consistency with federal guidance on mitigation banking, and defines a wetland mitigation site as a site where wetlands are restored, created, or enhanced, or in exceptional circumstances preserved expressly for the purpose of providing compensatory mitigation in advance of authorized impacts on similar resources.

Mitigation policy guidance (RCW 75.46) states that the guidance shall create procedures that provide for alternative mitigation measures that have a low risk to the environment, yet have a high net environmental, social, and economic benefit compared to status quo options.

Local Laws and Regulations

Counties and local jurisdictions in Washington regulate the construction of over-water structures through shoreline management codes, such as the King County Shoreline Management Code (*http://www.metrokc.gov/mkcc/Code/*) or the City of Bellevue Land Use Code (*http://www.ci.bellevue.wa.us/cobasp/lucindex.asp*). These codes are drafted in the spirit of and enacted in conformance with the Washington Administrative Code.

Available Guidance Materials for Construction and Operation of Over-Water Structures in Freshwater

In response to the recent Endangered Species Act listing of species, the Washington Department of Fish and Wildlife (WDFW), the Washington Department of Ecology (Ecology), the Washington Department of Transportation (WSDOT), the National Marine Fisheries Service (NMFS), and the U.S. Fish and Wildlife Service (USFWS) have begun to update existing guidance and develop new guidance for activities with the potential to adversely affect the environment. This guidance is intended to provide a holistic approach to aquatic resources, and is expected to have the flexibility needed to address watershed activities and salmon recovery efforts while operating within the existing regulatory framework.

The following list of available guidance for construction and operation of over-water structures is not comprehensive. Rather it is limited to the most recent guidelines or those currently under revision.

- *Guidance for Endangered Species Act Section 7 Consultation—Effect Determinations for New and Replacement Piers and Bulkheads in Lake Washington*, July 24, 2000. This document was prepared by the NMFS and provides background and guidance for effect determinations for new and replacement piers and bulkheads proposed for urbanized lakes, with emphasis on Lake Washington. The effect determination guidance used in this document is addressed in two separate documents: *A Guide to Biological Assessments*, March 23, 1999, and *The Habitat Approach,* August 26, 1999

- *Alternative Mitigation Policy Guidance*, February 10, 2000. This guidance was cooperatively developed by Ecology, WDFW, and WSDOT under the auspices of the Salmon Recovery Act (RCW 75.46), in order to improve the ecological benefits of compensatory mitigation for project impacts on wetlands, water quality, and fish and wildlife.

- *A Citizen's Guide to the 4(d) Rule for Threatened Salmon and Steelhead on the West Coast*, June 2000. This guide introduces and explains the rule and provides a user-friendly description of why the rule is needed, what it contains, how it will affect citizens, and how to obtain more information: (*http://www.nwr.noaa.gov/1salmon/salmesa/4ddocs/citguide.htm#Take%20Guidance*).

- *Best Management Practices to Protect Water Quality from Non-Point Source Pollution*, March, 2000. This document was prepared by Warrington (2000). It is an open-ended document produced as a web site so that it can be readily updated and expanded. The document provides recommendations that have been compiled from readily available published documents and internet sites and from some gray literature that may not be as readily available. Citations, references, and web links are provided. The document is organized by sectors. Under the service industries sector, guidelines for best management practices for the construction of wharves, docks, piers, and floats are provided (*http://www.nalms.org/bclss/bmphome.html*).

Recommendations for Guidance Document

Shore-zone development in general modifies and degrades the environment, thereby adversely affecting wildlife and fish species. The observed responses discussed in this paper (i.e., predation, behavior, and habitat structures) confirm this fact. The resultant modification and degradation of the environment occur through the following mechanisms: shore-zone habitat structure changes, shading and ambient light changes, disruption of water flow pattern and energy, and physical-chemical environmental disruptions. However, some site-specific and species-specific responses still require further research. This research is needed to obtain information required to close existing data gaps, thereby gaining a better understanding of the mechanisms of disruption associated with all over-water structures. The following recommendations are intended for the development of future policy and guidance documents that address the environmental impacts of over-water structures and associated construction and operation activities.

General Policies

- A greater statewide level of coordination among local jurisdictions, state agencies, and federal agencies is needed in the preparation of guidelines for the maintenance, construction, and operation of over-water structures.

- Statewide guidelines are needed to protect ecosystem functions and direct habitat impact mitigation, resource management, and project planning. However, because of the hydrological characteristics of the systems and differences in fish habitat utilization, two separate sets of guidelines should be developed for eastern and western Washington.

- All new rules, regulations, and guidelines for over-water structures should be supported with scientific data.

- Future research should be focused on areas where gaps and ambiguities have been identified, and resources should be allocated for this purpose.

- Existing shoreline conditions (e.g., riparian and shallow-water) should be documented by videotaping to facilitate detection of unpermitted development activities. More intensive supervision and enforcement of shoreline use and inspection of proposed projects during construction should be implemented.

- In highly developed systems, such as Lake Washington in western Washington and Lake Chelan in eastern Washington, no net increase in over-water coverage should be allowed. In such systems, offsite mitigation alternatives (e.g., in areas with the lowest development density) should be favored over onsite mitigation whenever the expected benefit is more cost-effective and yields greater ecological benefit.

- Preference should be given to offsite mitigation efforts consolidated on one site versus multiple offsite locations.

- All mitigation should provide better functional value than that provided by the habitat being replaced.

- If new over-water structures are to be allowed, the mitigation measures required to compensate for the construction of such structures should include site- and project-specific research to verify “not likely to adversely affect” situations prior to project implementation.

- For new and retrofitting projects, strict monitoring and evaluation programs should be required and included in the project plans. Third-party groups should conduct the monitoring and evaluation programs to preclude bias in the process.

- During the evaluation of proposed projects, a policy allowing no new over-water structures should first be considered. Because of their smaller surface area and correspondingly smaller shade effect, buoys should be selected rather than piers and docks for recreational mooring.

- There should be a greater level of regulation for activities such as boating that have interrelated effects. Funds from taxation imposed on such activities should be directed to shoreline restoration and enhancement programs.

Shore-Zone Development

- To provide maximum protection to juvenile chinook salmon in eastern and western Washington, further development in existing undeveloped shore-zone areas should be restricted, particularly in those areas having the characteristics preferred by this species (i.e., low-gradient habitats with sandy bottom and no aquatic vegetation).

- The goals and objectives of shore-zone restoration projects should include habitat characteristics, functionality, and values consistent with the preferred habitat for chinook salmon.

- New research should be initiated to investigate the preferred habitat characteristics for other salmonid species and their prey.

- Minimum setbacks should be established to help prevent shoreline and stream bank erosion and to help minimize the cumulative effects of shore-zone development. These required setbacks could include requirements for the relocation of existing structures that may already exist within designated setbacks.

- Additional research should be conducted to study the effectiveness of salmon habitat restoration projects in lakes and slow-flowing rivers and reservoirs.

Structure Size

- To minimize the cumulative effects of over-water structures, in particular the loss of habitat and the potential creation of refuge for predators, all structures should be as narrow as possible to achieve the project purpose. In addition, the multifamily use of individual docks should be encouraged, and only one dock per multi-lot development should be allowed.

- The number and body size of organisms using an area influenced by a floating object are directly related to the surface area of the object. Therefore, if a new over-water structure is to be allowed, the minimum possible size should be used to minimize the attraction of salmonid predators such as bass.

On-Water Structures

- Guidelines specifically addressing the storage and operation of on-water structures (i.e., log booms and rafts, trash-booms and trash-racks, work barges, and houseboats) should be prepared. Until structure-specific data become available, the responses observed from over-water structures should be extrapolated, particularly regarding changes in ambient light and in habitat function.

Pilings

- Smallmouth bass and largemouth bass have a strong affinity to pilings. Therefore, for all new projects, and for retrofitting projects when feasible from an engineering perspective, a downgrade in size and number of pilings should be required in order to minimize potential predation on juvenile salmonids.

- Pier and dock pilings, which intercept gravel transport, may accelerate beach erosion. Therefore, the use of buoy and anchor systems should be preferred over pilings to prevent beach erosion.

- In order to minimize the potential for predation on juvenile salmonids in free-flowing areas of systems where northern pikeminnow occur, the placement of in-water structures that create back-eddies and low-velocity microhabitat should not be allowed.

- Pile-driving activities should be regulated, not because of potential noise impact, which seems to be negligible for salmonids, but for the potential to disturb bottom sediments.

- The 300-foot protection zone restricting pile-driving activities in the vicinity of known sockeye spawning areas also should be required for chinook salmon in known beach spawning areas of Lake Washington.

Bulkheads and Riprap

- New bulkheads should not be permitted under any circumstance; instead, bioengineering solutions should be required.

- For retrofitting projects, bulkheads should be completely eliminated when possible or relocated shoreward of ordinary high water, and shorelines should be restored with emergent and riparian plant species.

- Riprap should not be allowed as an erosion control measure. Instead, site-specific bioengineering techniques should be required when alteration of the natural shoreline conditions is unavoidable, or for retrofitting projects.

Shoreline Vegetation

- If the over-water structure is permitted, onsite, in-kind, offsite, or out-of-kind mitigation (or any combination of these) should be required to achieve no-net-loss of habitat. This mitigation should include the establishment of native vegetation on any disturbed and adjacent shoreline areas, to minimize the adverse effects associated with cumulative loss of shoreline vegetation.

- A buffer should be preserved between new upland developments associated with over-water structures and the shoreline, to protect foraging and rearing habitat for fish and wildlife.

- Shoreline development associated with the construction of an over-water structure should not include the alteration of natural stable shorelines or the creation of manicured land that extends to the river or lake edge. In already altered shoreline areas, bioengineering techniques should be used to protect altered shorelines.

Ambient Light and Shading

- Given that shading can affect habitat function by creating visual barriers to migrating fish, new and retrofitted over-water structures should be required to incorporate design elements to minimize the shaded area under the structure.

- New dock design elements currently required in eastern Washington (e.g., ambient light grids, white PVC sleeves for pilings, bright reflective aluminum, and bright white materials for flotation) should be investigated to determine their efficacy in reducing salmonid predation and in allowing adequate light penetration for macrophyte production. If found to be effective, these elements also should be required for projects in western Washington.

- Accessory dock structures such as pier skirting and batter boards that increase shading impacts on aquatic vegetation should not be permitted in the design or construction of new docks.

Water Quality

- Because the reaction distance declines as a decaying power function of turbidity, maintenance of background turbidity levels should be required during construction, to avoid potential adverse effects on salmonid predation. This can be achieved, for example, by the use of silt curtains or cofferdams.

- Because leachate from treated wood is toxic to aquatic organisms, the use of treated wood should not be allowed in construction of over-water structures.

References

1. ADFG. 1996. Streambank revegetation and protection: A guide for Alaska. Alaska Department of Fish and Game. Obtained from agency web site: *http://www.state.ak.us/local/akpages/FISH.GAME/habitat/geninfo/webpage/techniques.htm*.

2. Anglea, Steven M. 1997. Abundance, food habits, and salmonid fish consumption of smallmouth bass and distribution of crayfish in Lower Granite Reservoir, Idaho–Washington. Masters thesis, University of Idaho.

3. Bauer, W. 1973. Management policies within the shore-process corridor, planning and management approaches to protect our shore-resource heritage. Whatcom County, Washington citizens committee (as cited by Mulvihill et al. 1980).

4. Beamesderfer, Raymond C. and Bruce E. Rieman. 1988. Predation by resident fish on juvenile salmonids in a mainstem Columbia reservoir: Part III, abundance and distribution of northern squawfish, walleye, and smallmouth bass. pp. 211–248 in: Predation by Resident Fish on Juvenile Salmonids in John Day Reservoir, 1983–86. Edited by T.P. Poe and B.E. Rieman. Bonneville Power Administration, Portland, Oregon.

5. Beauchamp, David A., Earl R. Byron, and Wayne A. Wurtsbaugh. 1994. Summer habitat use by littoral-zone fishes in Lake Tahoe and the effects of shoreline structures. North American Journal of Fisheries Management 14:385–394.

6. Bennett, D.H., T.J. Dresser, Jr., and T.S. Curet. 1992. Abundance of subyearling chinook salmon in Little Goose Reservoir, Washington, spring 1991. Prepared for U.S. Army Corps of Engineers, Walla Walla, Washington.

7. Beschta, Robert L., William S. Platts, J. Boone Kauffman, and Mark T. Hill. 1994. Artificial stream restoration—Money well spent or an expensive failure? pp. 76–104 in: Proceedings of the Universities Council on Water Resources: Environmental Restoration. UCOWR 1994 annual meeting, Big Sky, Montana, August 2–5, 1994.

8. Bonham, A.J. 1983. The management of wave-spending vegetation as bank protection against boat wash. Landscape Planning 10:15–30.

9. Brown, A.M. 1998. Shoreline residential development and physical habitat influences on fish density at the lake edge of Lake Joseph, Ontario, Canada. M.S. thesis. University of Toronto, Ontario.

10. Bryan, Michael D. and Dennis L. Scarnecchia. 1992. Species richness, composition, and abundance of fish larvae and juveniles inhabiting natural and developed shorelines of a glacial Iowa lake. Environmental Biology of Fishes 35:329–341.

11. Buck, D.H. 1956. Effects of turbidity on fish and fishing. Transactions North American Wildlife Confederation 21:249–261.

12. Campbell, H.J. 1954. The effect of siltation from gold dredging on the survival of rainbow trout and eyed eggs in Powder River, Oregon. Oregon State Game Commission (as cited by Warrington 1999a).

13. Carlson, Thomas J. 1996. The characterization of underwater infrasound generated by vibratory pile driving within the context of the characteristics of sound known to result in avoidance response by juvenile salmonids. Appendix A report prepared for Oregon State University. 19 pp. U.S. Army Corps of Engineers.

14. Carlson, Thomas J. 1997. Characterization of underwater sound generated by impact pile driving within the context of the response of salmonids to impulsive sound. Draft report not approved for public release, limited distribution. Technical report EL-97-?? U.S. Army Corps of Engineers, Waterways Experiment Station, Fisheries Engineering Team, Columbia River Basin, Stevenson, Washington. Prepared for U.S. Army Engineer District, Portland, Oregon.

15. Carlson, Thomas. September 13, 2000. Personal communication (telephone conversation with José Carrasquero, Herrera Environmental Consultants, regarding effects of pile driving on fishes.) Battelle Pacific Northwest National Laboratory, Richland, Washington.

16. Carrasquero, José. 1997. Unpublished field observations made during daytime and nighttime snorkeling surveys for fish population assessment. Surveys conducted in many stream tributaries in the Puget Sound region, on the Olympic peninsula and in the foothills of the Cascade range. Fisheries biologist, National Marine Fisheries Service, Montlake office, Seattle, Washington.

17. Carrasquero, José. 2000. Unpublished field observations made during daytime snorkeling surveys for fish utilization of shoreline areas. Surveys conducted in the vicinity of docks, piers, and bulkheads, in eastern and western Washington. Fisheries biologist, Herrera Environmental Consultants, Seattle, Washington.

18. Cederholm, C.J., D.H. Johnson, R.E. Bilby, L.G. Dominguez, A.M. Garret et al. 2000. Pacific salmon and wildlife—ecological contexts, relationships, and implications for management. Special edition technical report. Prepared for D.H. Johnson and T.A. O’Neil, Wildlife–habitat relationships in Oregon and Washington. Washington Department of Fish and Wildlife, Olympia.

19. Chmura, Gail L. and Neil W. Ross. 1978. The environmental impacts of marinas and their boats: a literature review with management considerations. University of Rhode Island, Marine Advisory Service, Narragansett.

20. Christensen, David L., Brian R. Herwig, Daniel E. Schindler, and Stephen R. Carpenter. 1996. Impacts of lakeshore residential development on coarse woody debris in north temperate lakes. Ecological Applications 6(4):1143–1149.

21. Colle, D.E., R.L. Cailteux, and J.V. Shireman. 1989. Distribution of Florida largemouth bass in a lake after elimination of all submersed aquatic vegetation. North American Journal of Fisheries Management 9:213–218.

22. Collins, Nicholas C., Peter St. Onge, and Vicki Dodington. 1995. The importance to small fish of littoral fringe habitat (Z<0.2m) in unproductive lakes, and the impacts of shoreline development. Lake and Reservoir Management 11:129 (abstract only).

23. Collis, Ken, Roy E. Beaty, and Bradford R. Crain. 1995. Changes in catch rate and diet of northern squawfish associated with the release of hatchery-reared juvenile salmonids in a Columbia River reservoir. North American Journal of Fisheries Management 15:346–357.

24. Cooper, William E. and Larry B. Crowder. 1979. Patterns of predation in simple and complex environments. pp. 257–267 in: Predator–prey systems in fisheries management. Edited by H. Clepper. Sport Fishing Institute, Washington, D.C.

25. Council on Environmental Quality. 1997. Considering cumulative effects under the National Environmental Policy Act. Executive Office of the President.

26. Crossman, E.J. 1959. Distribution and movements of a predator, the rainbow trout, and its prey, the redside shiner, in Paul Lake, British Columbia. J. Fish. Res. Bd. Can. 16:24267.

27. Curet, T. 1993. Habitat use, food habits, and the influence of predation on subyearling chinook salmon in Lower Granite and Little Goose reservoirs. Masters thesis. University of Idaho, Moscow.

28. Dauble, D.D., T.L. Page, and R.W. Hanf, Jr. 1989. Spatial distribution of juvenile salmonids in the Hanford reach, Columbia River. U.S. National Marine Fisheries Service Bulletin 87:775–790.

29. DiCostanzo, A.J. 1957. Growth of bluegill (*Lepomis macrochirus*) and pumkinseed (*Lepomis gibbosus*) of Clear Lake, Iowa. Iowa State Coll. J. Sci. 32: 19-34.

30. Donald, D.B. and J. Alger. 1993. Geographic distribution, species displacement, and niche overlap for lake trout and bull trout in Montana lakes. Can. J. Zool. 71:238–247.

31. Ecology et al. 1994. Guidelines for developing freshwater wetlands mitigation plans and proposals. Publication #94-29. Washington Department of Ecology, Washington Department of Fisheries, Washington Department of Wildlife, U.S. Environmental Protection Agency, U.S. Army Corps of Engineers, and U.S. Fish and Wildlife Service.

32. Ecology. 1998. How Ecology regulates wetlands. An introduction to regulatory authority, wetland definitions and delineation, wetland characterization and function assessment, wetland mitigation, buffers, and more. Publication No. 97-112. Washington Department of Ecology, Olympia. Available at *http://www.wa.gov/ecology* under Shorelands and Wetlands.

33. Everest, F.H. and J.R. Sedell. 1984. Evaluation of fisheries enhancement projects on Fish Creek and Wash Creek, 1982 and 1983. Bonneville Power Administration, Division of Fish and Wildlife, Portland, Oregon.

34. Faler, Micheal P., Lawrence M. Miller, and Kurt I. Welke. 1988. Effects of variation in flow on distributions of northern squawfish in the Columbia River below McNary Dam. North American Journal of Fisheries Management 8:30–35.

35. Fay, Richard. 1997. What fish hear. pp. 77–90 in: Using Sound to Modify Fish Behavior at Power-Production and Water-Control Facilities: A Workshop. December 12–13, 1995, Portland State University, Portland, Oregon. Phase II, final report. Edited by Thomas J. Carlson and Arthur N. Popper. DOE/BP-62611-11. Prepared for U.S. Department of Energy; Bonneville Power Administration; Environment, Fish and Wildlife, Portland, Oregon.

36. Fayram, Andrew Hunter. 1996. Impacts of largemouth bass (*Micropterus salmoides*) and smallmouth bass (*Micropterus dolomieui*) predation on populations of juvenile salmonids in Lake Washington. Masters thesis. University of Washington, School of Fisheries, Seattle.

37. Fayram, A.H. and T.H. Sibley. 2000. Impact of predation by smallmouth bass on sockeye salmon in Lake Washington. N. Am. J. Fish. Manage. 20:81–89.

38. Feist, B.E., J.J. Anderson, and R. Miyamoto. 1996. Potential impacts of pile driving on juvenile pink (*Oncorhynchus gorbuscha*) and chum (*O. keta*) salmon behavior and distribution. FRI-UW-9603. Fisheries Research Institute, School of Fisheries, University of Washington, Seattle.

39. Fisher, Larry. November 9, 2000. Personal communication (information provided by fax to José Carrasquero, Herrera Environmental Consultants, regarding sightings of beach spawning chinook salmon on Mercer Island in Lake Washington). Washington Department of Fish and Wildlife.

40. Fissell, C.A. and R.K. Nawa. 1992. Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. North American Journal of Fisheries Management 12:182–197.

41. Fraley, J.J. and B.B. Shepard. 1989. Life history, ecology and population status of migratory bull trout (*Salvelinus confluentus*) in the Flathead Lake and river system, Montana. Northwest Science 63:133–143.

42. Fresh, Kurt. June 2, 1999. Personal communication (telephone conversation with José Carrasquero, Herrera Environmental Consultants, regarding adult salmon migration routes in Lake Union). Washington Department of Fish and Wildlife, Olympia.

43. Fresh, Kurt. November 2000. Personal communication (review comments forwarded by the state salmon recovery program steering committee to José Carrasquero, Herrera Environmental Consultants, regarding the draft white paper on over-water structures [freshwaters]). Washington Department of Fish and Wildlife, Olympia.

44. Garland, R.D. and K.F. Tiffan. 1999. Nearshore habitat use by subyearling fall chinook salmon in the Snake River. pp. 51–70 in: Post-Release Attributes and Survival of Hatchery and Natural Fall Chinook Salmon in the Snake River, Annual Report 1998 to Bonneville Power Administration, Portland, Oregon. Edited by K.F. Tiffan, D.W. Rondorf, W.P. Connor, and H.L. Burge. DOE/BP-21708-7. 203 pp.

45. Ginetz, R.M., and P.A. Larkin. 1976. Factors affecting rainbow trout (*Salmo gairdneri)* predation on migrant fry of sockeye salmon (*Oncorhynchus nerka*). J. Fish. Res. Bd. Canada 33:19–24.

46. Godin, Jean-Guy J. 1981. Migrations of salmonid fishes during early life history phases: daily and annual timing. in: Proceedings of the Salmon and Trout Migratory Behavior Symposium, first international symposium, June 3–5, 1981. Edited by E.L. Brannon and E.O. Salo. University of Washington, School of Fisheries, Seattle.

47. Goetz, F. 1989. Biology of bull trout (*Salvelinus confluentus*): A literature review. Willamette National Forest, Eugene, Oregon.

48. Goetz, F. 1997. Distribution of bull trout in Cascade mountain streams of Oregon and Washington. pp. 237–248 in: Friends of the Bull Trout Conference Proceedings. Edited by W.C. Mackay, M.K. Brewin, and M. Monita. Bull Trout Task Force (Alberta), c/o Trout Unlimited Canada, Calgary.

49. Gray, G.A., G.M. Sonnevil, H.C. Hansel, C.W. Huntington, and D.E. Palmer. 1984. Feeding activity, rate of consumption, daily ration and prey selection of major predators in the John Day pool. U.S. Fish and Wildlife Service, Annual report (Contract DI-AI79-82BP34796). Cook, Washington.

50. Gray, Gerard A. and Dennis W. Rondorf. 1986. Predation on juvenile salmonids in Columbia basin reservoirs. pp. 178–185 in: Reservoir Fisheries Management: Strategies for the 80's. Edited by G.E. Hall and M.J. Van Den Avyle. American Fisheries Society, Southern Division, Reservoir Committee, Bethesda, Maryland.

51. Haines, T.A. and R.L. Butler. 1969. Responses of yearling smallmouth bass (*Micropterus dolomieui*) to artificial shelter in a stream aquarium. J. Fish. Res. Bd. Canada 26:21–31.

52. Healey, M.C. 1991. Life history of chinook salmon (*Oncorhynchus tshawytscha*). pp 311–393 in: Pacific Salmon Life Histories. Edited by C. Groot and L. Margolis. University of British Columbia Press, Vancouver.

53. Helfman, Gene S. 1979. Fish attraction to floating objects in lakes. pp. 49–57 in: Response of Fish to Habitat Structure in Standing Water. Edited by D.L. Johnson and R.A. Stein. Special publication 6. American Fisheries Society, North Central Division, Bethesda, Maryland.

54. Helfman, Gene S. 1981a. The advantage to fishes of hovering in shade: Copeia 1981(2):392–400.

55. Helfman, Gene S. 1981b. Twilight activities and temporal structure in a freshwater fish community. Can. J. Fish. Aquat. Sci. 38:1405–1420.

56. Helfman, Gene S., Bruce B. Collette, and Douglas E. Facey. 1997. The diversity of fishes. Blackwell Science, Inc.

57. Hilton, J. and G. L. Phillips. 1982. The effect of boat activity on turbidity in a shallow broadland river. Journal of Applied Ecology 19:143–150.

58. Hjort, R.C., B.C. Mundy, and P.L. Hulett. 1981. Habitat requirements for resident fishes in the reservoirs of the lower Columbia River. Report (contract DACW57-79-C-0067) to U.S. Army Corps of Engineers, Portland, Oregon (as cited by Beamesderfer and Rieman 1988).

59. Howe, Kate. 1997. Construction of artificial riffles and pools for freshwater habitat restoration. Restoration and Reclamation Review, University of Minnesota, Department of Horticultural Science.

60. Independent Scientific Group. 1996. Return to the river—Restoration of salmonid fishes in the Columbia River ecosystem (prepublication copy). Development of an alternative conceptual foundation and review and synthesis of science underlying the Columbia River Basin Fish and Wildlife Program of the Northwest Power Planning Council. September 10, 1996.

61. Jennings, Martin J., Michael A. Bozek, Gene R. Hatzenbeler, Edward E. Emmons, and Michael D. Staggs. 1999. Cumulative effects of incremental shoreline habitat modification on fish assemblages in north temperate lakes. North American Journal of Fisheries Management 19:18–27.

62. Kahler, Tom, Martin Grassley, and David Beauchamp. 2000. A summary of the effects of bulkheads, piers, and other artificial structures and shorezone development on ESA-listed salmonids in lakes. Final report, 13 July 2000. Prepared for the City of Bellevue, Washington by The Watershed Company, Kirkland, Washington, and Washington Cooperative Fish and Wildlife Research Unit, University of Washington, School of Fisheries, Seattle.

63. Kauffman, J.B., R.L. Beschta, and W.S. Platts. 1993. Fish habitat improvement projects in the Fifteenmile Creek and Trout Creek basins of central Oregon: Field review and management recommendations. DOE/BP-18955-1. U.S. Department of Energy, Bonneville Power Administration.

64. Key, L.O., R.D. Garland, and K. Kappenman. 1996. Nearshore habitat use by subyearling chinook salmon and non-native piscivores in the Columbia River. pp. 64–79 in: Identification of the Spawning, Rearing, and Migratory Requirements of Fall Chinook in the Columbia River Basin. 1994 Annual Report to Bonneville Power Administration, Portland, Oregon. Edited by D.W. Rondorf and K.F. Tiffan. Contract DE-AI79-91BP21708.

65. King County 2000. Selected ongoing and recent research on chinook salmon in the greater Lake Washington watershed. Conference held on November 8–9, 2000 in Seattle Washington by King County Department of Natural Resources, Wastewater Treatment Division.

66. Kinnison, Mike. June 29, 1999. Personal communication (email message exchange with José Carrasquero, Herrera Environmental Consultants, regarding chinook spawning sighting in Lake Union). University of Washington, School of Fisheries, Seattle, Washington.

67. Knutsen, Christopher J. and David L. Ward. 1991. Behavior of juvenile salmonids migrating through the Willamette River near Portland, Oregon. Information Reports Number 91-5. Oregon Department of Fish and Wildlife, Fish Division.

68. Knutson, P.L. 1987. Planting guidelines for marsh development and bank stabilization. Coastal Engineering Technical Aid No. 77-3. U.S. Army Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Virginia.

69. Knutson, P.L. 1988. Shore erosion control with salt marsh vegetation. Coastal Engineering Technical Aid No. 82-3. U.S. Army Corps of Engineers, Coastal Engineering Research Center, Vicksburg, Mississippi.

70. Lagler, K.F., A.S. Hazzard, W.E. Hazen, and W.A. Tompkins. 1950. Outboard motors in relation to fish behavior, fish production and angling success. pp. 280–303 in: Transactions of the 15th Annual North American Wildlife Conference.

71. Lange, M. 1999. Abundance and diversity of fish in relation to littoral and shoreline features. M.S. thesis. University of Guelph, Ontario, Canada.

72. Lewis, R.L. 1982. Creation and restoration of coastal plant communities. Third edition. CRC Press, Inc., Boca Raton, Florida.

73. Lorang, Mark S., Jack A. Stanford, F. Richard Hauer, and Jon H. Jourdonnais. 1993. Dissipative and reflective beaches in a large lake and the physical effects of lake level regulation. Ocean & Coastal Management 19:263–287.

74. Mace, P.M. 1983. Predatory-prey functional responses and predation by staghorn sculpins, *Leptocottus armatus* on chum salmon, *Oncorhynchus keta*. Doctoral dissertation, University of British Columbia, Vancouver, British Columbia (as cited by Tabor et al. 1998).

75. Matkowski, S.M.D. 1989. Differential susceptibility of three species of stocked trout to bird predation. North American Journal of Fisheries Management 9:184–187.

76. McDonald, J. 1960. The behavior of Pacific salmon fry during their downstream migration to freshwater and saltwater nursery areas. Journal Fisheries Research Board of Canada 17(5):655–676

77. McNeil, W. J. and W. H. Ahnell. 1964. Success of pink salmon spawning relative to size of spawning bed materials. Special scientific report, Fisheries., No. 469. U.S. Fish and Wildlife Service (as cited by Warrington 1999a).

78. McPhail, J.D. and J.S. Baxter. 1996. A review of bull trout (*Salvelinus confluentus*) life-history and habitat use in relation to compensation and improvement opportunities. Fisheries Management Report No 104. British Columbia Ministry of Environment, Lands and Parks.

79. Modde, Timothy, Anthony F. Wasowicz, and Dale K. Hepworth. 1996. Cormorant and grebe predation on rainbow trout stocked in a southern Utah reservoir. North American Journal of Fisheries Management 16:388–394.

80. Mueller, G. 1980. Effects of recreational river traffic on nest defense by longear sunfish. Transactions of the American Fisheries Society 109(2):248–251.

81. Mulvihill, E.L., C.A. Francisco, J.B. Glad, K.B. Kaster, and R.E. Wilson. 1980. Biological impacts of minor shoreline structures on the coastal environment: State of the art review, Volume II, data printout. FWS/OBS-77/51. Prepared by Beak Consultants, Inc., Portland, Oregon, with O. Beeman, for National Coastal Ecosystems Team, Office of Biological Services, Fish and Wildlife Service, U.S. Department of the Interior.

82. NMFS. 2000. Draft biological opinion. Reasonable and Prudent Measures section. National Marine Fisheries Service, Habitat Conservation Division, Lacey Washington.

83. Noggle, C. C. 1978. Behavioral, physiological and lethal effects of suspended sediment on juvenile salmonids. Masters thesis. University of Washington.

84. Pacific Northwest Pollution Control Council. 1971. Log storage and rafting in public waters. A task force report prepared by G. Hansen, Washington Department of Ecology; G. Carter, Oregon Department of Environmental Quality; W. Towne, Alaska Department of Environmental Conservation; and G. O'Neal, U.S. Environmental Protection Agency.

85. Palmer, D.E. 1982. Abundance, survival, distribution, and movements of selected fishes in lower Snake River reservoirs. Masters thesis. University of Idaho, Moscow (as cited by Beamesderfer and Rieman 1988).

86. Patten, Benjamin G. 1971. Increased predation by the torrent sculpin, *Cottus rhotheus*, on coho salmon fry, *Oncorhynchus kisutch*, during moonlight nights. Journal Fisheries Research Board of Canada 28(9):1352–1354.

87. Petersen, James H, Sally T. Sauter, Conrad N. Frost, Steven R. Gray, and Thomas P. Poe. 1993. Indexing juvenile salmonid consumption by northern squawfish in the Columbia River below Bonneville Dam and in John Day Reservoir, 1992. in: System-wide Significance of Predation on Juvenile Salmonids in Columbia and Snake River Reservoirs: Annual Report 1992. Edited by James H. Petersen and Thomas P. Poe. Prepared by U.S. Fish and Wildlife Service, National Fishery Research Center, Columbia River Field Station, Cook, Washington, for U.S. Department of Energy, Bonneville Power Administration.

88. Petersen, J.H. and D.M. Gadomski. 1994. Light-mediated predation by northern squawfish on juvenile chinook salmon. Journal of Fish Biology 45(supplement A):227–242.

89. Pflug, David E. 1981. Smallmouth bass (*Micropterus dolomieui*) of Lake Sammamish: a study of their age and growth, food and feeding habits, population size, movement and homing tendencies, and comparative interactions with largemouth bass. Masters thesis. University of Washington, College of Fisheries, Seattle.

90. Pflug, David E. and Gilbert P. Pauley. 1984. Biology of smallmouth bass (*Micropterus dolomieui*) in Lake Sammamish, Washington. Northwest Science 58(2):118–130.

91. Phinney, David Duane. 1999. Avian predation on juvenile salmonids in the Yakima River, Washington. Masters thesis. University of Washington, School of Fisheries, Seattle.

92. Poe, Thomas P., Hal C. Hansel, Steven Vigg, Douglas E. Palmer, and Linda A. Prendergast. 1991. Feeding of predaceous fishes on out-migrating juvenile salmonids in John Day Reservoir, Columbia River. Transactions of the American Fisheries Society 120(4):405–420.

93. Popper, Arthur N. 1997. Sound detection by fish: Structure and function. pp. 65–76 in: Using Sound to Modify Fish Behavior at Power-Production and Water-Control Facilities: A Workshop. December 12–13, 1995, Portland State University, Portland, Oregon. Phase II, final report. Edited by Thomas J. Carlson and Arthur N. Popper. DOE/BP-62611-11. Prepared for U.S. Department of Energy; Bonneville Power Administration; Environment, Fish and Wildlife, Portland, Oregon.

94. Popper, Arthur N. and Thomas J. Carlson. 1998. Application of sound and other stimuli to control fish behavior. Transactions of the American Fisheries Society 127(5):673–707.

95. Quinn, Thomas. June 16, 1999. Personal communication (email message exchange with José Carrasquero, Herrera Environmental Consultants, regarding fish usage and chinook spawning sighting in Lake Union). University of Washington, School of Fisheries, Seattle, Washington.

96. Ratliff, D.E., S.L. Thiesfeld, W.G. Weber, A.M. Stuart, M.D. Riehle, and D.V. Buchanan. 1996. Distribution, life history, abundance, harvest, habitat, and limiting factors of bull trout in the Metolius River and Lake Billy Chinook, Oregon, 1983–4. Inland Fisheries Report 96-7. Oregon Department of Fish and Wildlife, Portland.

97. Reeves, G.H. and T.D. Roelofs. 1982. Influence of forest and rangeland management on anadromous fish habitat in western North America—Rehabilitation and enhancing stream habitat: 2. Field applications. General technical report PNW-140. U.S. Department of Agriculture, Forest Service.

98. Rieman, B.E. and J.D. McIntyre. 1993. Demographic habitat requirements for conservation of bull trout. Gen. Tech. Rep. INT-302. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, Utah.

99. Rolletschek, Hardy and Harald Kühl. 1997. Die Auswirkungen von Röhrichtschutzbauwerken auf die Gewässerufer (The impacts of reed protecting structures on lakesides). Limnologica 27(3–4):365–380.

100. Rondorf, Dennis W., Gerard A. Gray, and Robert B. Fairley. 1990. Feeding ecology of subyearling chinook salmon in riverine and reservoir habitats of the Columbia River. Transactions of the American Fisheries Society 119:16–24.

101. Sand, Olav. 1997. Infrasonic detection by fish. pp. 91–105 in: Using Sound to Modify Fish Behavior at Power-Production and Water-Control Facilities: A Workshop. December 12–13, 1995, Portland State University, Portland, Oregon. Phase II, final report. Edited by Thomas J. Carlson and Arthur N. Popper. DOE/BP-62611-11. Prepared for U.S. Department of Energy; Bonneville Power Administration; Environment, Fish and Wildlife, Portland, Oregon.

102. Schaumburg, Frank D. 1973. The influence of log handling on water quality. Environmental Protection Technology Series, EPA-R2-73-085. Prepared for U.S. Environmental Protection Agency, Office of Research and Monitoring, Washington, D.C.

103. Schmude, Kurt L., Martin J. Jennings, Keith J. Otis, and Randal R. Piette. 1998. Effects of habitat complexity on macroinvertebrate colonization of artificial substrates in north temperate lakes. Journal of the North American Benthological Society 17(1):73–80.

104. Schollen, Mark. 1995. Alternative shoreline treatments to achieve ecosystem objectives. Lake and Reservoir Management 11:187–188 (abstract only).

105. Schuytema, Gerald S. and Robert D. Shankland. 1976. Effects of log handling and storage on water quality. Environmental Protection Technology Series, EPA-600/2-76-262. U.S. Environmental Protection Agency, Office of Research and Development, Industrial Environmental Research Laboratory, Cincinnati, Ohio.

106. Shively, R.S., R.A. Tabor, R.D. Nelle, D.B. Jepsen, J.H. Petersen, S.T. Sauter, and T.P. Poe. 1991. System-wide significance of predation on juvenile salmonids in the Columbia and Snake river systems. U.S. Fish and Wildlife Service, Annual Report. Project 90-078 (Contract DE-AI79-90BP07096). Cook, Washington.

107. Simenstad, Charles A., Barbara J. Nightingale, Ronald M. Thom, and David K. Shreffler. 1999. Impacts of ferry terminals on juvenile salmon migrating along Puget Sound shorelines—Phase I: Synthesis of state of knowledge. Prepared by Washington State Transportation Center (TRAC), Seattle, for Washington State Transportation Commission and in cooperation with U.S. Department of Transportation, Federal Highway Administartion.

108. Stein, Jefferey N. 1970. A study of the largemouth bass population in Lake Washington. Masters thesis. University of Washington, College of Fisheries, Seattle.

109. Tabor, Roger A., Rip S. Shively, and Thomas P. Poe. 1993. Predation on juvenile salmonids by smallmouth bass and northern squawfish in the Columbia River near Richland, Washington. North American Journal of Fisheries Management 13:831–838.

110. Tabor, Roger A., Gayle Brown, and Victoria T. Luiting. 1998. The effect of light intensity on predation of sockeye salmon fry by prickly sculpin and torrent sculpin. U.S. Fish and Wildlife Service, Western Washington Office, Aquatic Resources Division, Lacey, Washington.

111. Tabor, Roger, Francine Mejia, and David Low. 2000. Predation of juvenile salmon by littoral fishes in the Lake Washington–Lake Union ship canal, preliminary results. Prepared for presentation at the American Fisheries Society, North Pacific International Chapter. 2000 conference, April 10–12, 2000, Mount Vernon, Washington.

112. Thomas, C.D. 1994. Extinction, colonization, and metapopulations: Environmental tracking by rare species. Conservation Biology 8(2):373–378.

113. Underwood, A.J. 1991. Beyond BACI: Experimental designs for detecting human environmental impacts on temporal variations in natural populations. Aust. J. Mar. Freshwater Res. 42:569–587.

114. USDA-FS 2000. Soil bioengineering, an alternative for roadside management—A practical guide. U.S. Department of Agriculture, Forest Service, San Dimas, California Technology & Development Center. Obtained from agency web site: *http://www.wsdot.wa.gov/EESC/CAE/design/Roadside/Soil%20bioeng.pdf*.

115. USDA-SCS. 1992. Engineering field handbook. U.S. Department of Agriculture, Soil Conservation Service.

116. USEPA. 1993. Guidance specifying management measures for sources of non-point pollution in coastal waters. Publication #840-B-92-002. U.S. Environmental Protection Agency, Office of Water, Washington, D.C. January 1993.

117. USEPA 2000. Principles for the ecological restoration of aquatic resources. EPA841-F-00-003. U.S. Environmental Protection Agency, Office of Water (4501F), Washington, D.C. Obtained from agency web site: *http://www.epa.gov/owow/wetlands/restore/principles.html.*

118. USFWS, NMFS, and WDFW. 1999. Memorandum of agreement between Washington State Department of Fish and Wildlife and National Marine Fisheries Service and U.S. Fish and Wildlife Service. [agreement regarding Endangered Species Act compliance for construction projects]. September 1999.

119. Vigg, S., T.P. Poe, L.A. Prendergast, and H.C. Hansel. 1991. Rates of consumption of juvenile salmonids and alternative prey fish by northern squawfish, walleyes, smallmouth bass, and channel catfish in John Day Reservoir, Columbia River. Transactions of the American Fisheries Society 120:421–438.

120. Vogel, Jason L. and David A. Beauchamp. 1999. Effects of light, prey size, and turbidity on reaction distances of lake trout (*Salvelinus namaycush*) to salmonid prey. Can. J. Fish. Aquat. Sci. 56:1293–1297.

121. Ward, David L., Anthony A. Nigro, Ruth A. Farr, and Christopher J. Knutsen. 1994. Influence of waterway development on migrational characteristics of juvenile salmonids in the lower Willamette River, Oregon. North American Journal of Fisheries Management 14:362–371.

122. Ward, David L., James H. Petersen, John J. Loch. 1995. Index of predation on juvenile salmonids by northern squawfish in the lower and middle Columbia River and in the lower Snake River. Transactions of the American Fisheries Society 124:321–334.

123. Warner, E. July 7, 2000. Personal communication (written comments to Tom Kahler, The Watershed Company). Muckleshoot Indian Tribe, Fisheries Division (as cited by Kahler et al. 2000).

124. Warner, K. 1972. Further studies of fish predation of salmon stocked in Maine lakes. Progressive Fish-Culturist 34:217–221.

125. Warrington, Patrick D. 1999a. Impacts of recreational boating on the aquatic environment. Posted on the North American Lake Management Society web site: *http://www.nalms.org/bclss/impactsrecreationboat.htm*.

126. Warrington, Patrick D. 1999b. Impacts of outboard motors on the aquatic environment. Posted on the North American Lake Management Society web site: *http://www.nalms.org/bclss/impactsoutboard.htm*.

127. Warrington, Patrick D. 2000. Best management practices to protect water quality from non-point source pollution. Posted on the North American Lake Management Society web site: *http://www.nalms.org/bclss/bmphome.html*.

128. Washington, state of. 2000. Alternative mitigation policy guidance: Interagency implementation agreement. February 10, 2000. Department of Fish and Wildlife, Department of Ecology, and Department of Transportation. 20 pp.

129. WDF. January 13, 1981. Memorandum by Phil Kauzloric to the Lake Washington file regarding lakeshore spawning sockeye and pile driving, containing estimate of explosives-generated energy transmission provided by Russ Webb (WDF Engineering). Washington Department of Fisheries, Natural Production Division.

130. WDFW. Undated[a]. WDFW salmonid predation reduction measures and dock specifications for north central Washington waters inhabited by federally listed fish species. Unpublished document provided by Bob Steele, area habitat biologist, Washington Department of Fish and Wildlife, Habitat Management Program, Region 3, Wenatchee, Washington.

131. WDFW. Undated[b]. Some typical WDFW salmonid predation reduction measures and/or hydraulic project approval (HPA) dock requirements on north central Washington waters inhabited by listed fish species protected under the federal Endangered Species Act. Unpublished document provided by Bob Steele, area habitat biologist, Washington Department of Fish and Wildlife, Habitat Management Program, Region 3, Wenatchee, Washington.

132. WDFW. Undated[c]. Recommendations for siting marinas and other over-water structures in the lower Columbia River. 2 pp. Unpublished document provided by Bob Steele, area habitat biologist, Washington Department of Fish and Wildlife, Habitat Management Program, Region 3, Wenatchee, Washington.

133. WDFW. Undated[d]. Conditions for siting of marinas and boat docks in waters containing anadromous fish. 4 pp. Unpublished document provided by Bob Steele, area habitat biologist, Washington Department of Fish and Wildlife, Habitat Management Program, Region 3, Wenatchee, Washington.

134. WDFW. 2000. Integrated streambank protection guidelines – (draft 8/22/2000). Washington Department of Fish and Wildlife, Washington Department of Transportation, and Washington Department of Ecology. Posted on Washington Department of Fish and Wildlife web site: *http://www.wa.gov/wdfw/hab/salguide/ispgdoc.htm#ch1*.

135. White, Steven T. 1975. The influence of piers and bulkheads on the aquatic organisms in Lake Washington. Masters thesis. University of Washington, College of Fisheries, Seattle.

136. Wood, C.C. and C.M. Hand. 1985. Food-searching behavior of the common merganser (*Mergus merganser*) I: functional response to prey and predator density. Canadian Journal of Zoology 63:1260–1270.

137. Würsig, B., C.R. Greene, Jr., and T.A. Jefferson. 2000. Development of an air bubble curtain to reduce underwater noise of percussive piling. Marine Environmental Research 49:79–93.

138. Wydoski, R.S. and R.R. Whitney. 1979. Inland fishes of Washington. University of Washington Press, Seattle, Washington.

139. Yousef, Y.A. 1974. Assessing effect on water quality by boating activity. USEPA/670/2-74-072. Prepared for U.S. Environmental Protection Agency, National Environmental Research Center (as cited by Warrington 1999a).

APPENDIX A

Literature Consulted and Other Sources of Information

Literature Consulted and Other Sources of Information

Able, Kenneth W., John P. Manderson, and Anne L. Studholme. 1998. The distribution of shallow water juvenile fishes in an urban estuary: the effects of manmade structures in the lower Hudson River. Estuaries 21(4B):731–744.

Allen, George H. Mortality of coho smolts migrating through a lake system. 1968. Ecology 49(5):1001–1002.

Bax, Nicholas J., Ernest O. Salo, and Bruce P. Snyder. 1980. Salmonid outmigration studies in Hood Canal: Final report, Phase V, January to July 1979. FRI-UW-8010. Prepared by the Fisheries Research Institute, College of Fisheries, University of Washington, for the U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Beauchamp, David Anthony. 1987. Ecological relationships of hatchery rainbow trout in Lake Washington. Ph.D. dissertation. University of Washington, School of Fisheries, Seattle.

Bevelhimer, Mark S. 1996. Relative importance of temperature, food, and physical structure to habitat choice by smallmouth bass in laboratory experiments. Transactions of the American Fisheries Society 125:274–283.

Bonneville Power Administration. 1997. Using sound to modify fish behavior at power-production and water-control facilities: A workshop. December 12–13, 1995, Portland State University, Portland, Oregon. Phase II, final report. Edited by Thomas J. Carlson and Arthur N. Popper. DOE/BP-62611-11. Prepared for U.S. Department of Energy; Bonneville Power Administration; Environment, Fish and Wildlife, Portland, Oregon.

Chapman, D.W. 1986. Salmon and steelhead abundance in the Columbia River in the nineteenth century. Transactions of the American Fisheries Society 115:662–670.

Costa, H.H. 1979. The food and feeding chronology of yellow perch (*Perca flavescens*) in Lake Washington. Int. Revue ges. Hydrobiol. 64(6):783–793.

Duncan, Rea E. 1956. Use of infrared radiation in the study of fish behavior. Special scientific report—Fisheries No. 170. U.S. Department of the Interior, Fish and Wildlife Service.

Eggers, D.M., N.W. Bartoo, N.A. Rickard, R.E. Nelson, R.C. Wissmar, R.L. Burgner, and A.H. Devol. 1978. The Lake Washington ecosystem: The perspective from the fish community production and forage base. Journal Fisheries Research Board of Canada 35:1553–1571.

Fresh, Kurt L. 1994. Lake Washington fish: A historical perspective. Lake and Reservoir Management 9(1–2):148-151.

Heiser, David W. and Earl L. Finn, Jr. 1970. Observations of juvenile chum and pink salmon in marina and bulkheaded areas. Supplemental progress report, Puget Sound stream studies. Washington Department of Fisheries, Management and Research Division.

Kruse, Heidi Katrina. 1998. Environmental factors affecting phytoplankton assemblages on the lower Snake impoundment series, Washington (abstract only). Masters thesis, Washington State University.

Levings, C.D., K. Conlin, and B. Raymond. 1991. Intertidal habitats used by juvenile chinook salmon (*Oncorhynchus tshawytscha*) rearing in the north arm of the Fraser River estuary. Marine Pollution Bulletin 22(1):20–26.

Lynch, William E., Jr. and David L. Johnson. 1989. Influences of interstice size, shade, and predators on the use of artificial structures by bluegills. North American Journal of Fisheries Management 9:219–225.

McMahon, T.E. and S.H. Holanov. 1995. Foraging success of largemouth bass at different light intensities: Implications for time and depth of feeding. Journal of Fish Biology 46:759–767.

Meehan, William R., Merlyn A. Brusven, and John F. Ward. 1987. Effects of artificial shading on distribution and abundance of juvenile chinook salmon (*Oncorhynchus tshawytscha*). Great Basin Naturalist 47(1):22–31.

Modde, Timothy, Anthony F. Wasowicz, and Dale K. Hepworth. 1996. Cormorant and grebe predation on rainbow trout stocked in a southern Utah reservoir. North American Journal of Fisheries Management 16:388–394.

Nordstrom, Karl F. 1989. Erosion control strategies for bay and estuarine beaches. Coastal Management 17:25–35.

North American Lake Management Society. 2000. Impacts of recreational boating on the aquatic environment; and best management practices to protect water quality from non-point source pollution (March 2000). Information posted on North American Lake Management Society web site: *http://www.nalms.org*.

Ratté, L.D. and E.O. Salo. 1985. Under-pier ecology of juvenile Pacific salmon (*Oncorhynchus* spp.) in Commencement Bay, Washington. Final report—December 1983 to December 1985. FRI-UW-8508. Prepared for the Port of Tacoma. December 1985.

Ratté, Lawrence Dennis. 1985. Under-pier ecology of juvenile Pacific salmon (*Oncorhynchus* spp.) in Commencement Bay, Washington. Masters thesis. University of Washington, School of Fisheries, Seattle.

Raymond, Howard L. 1988. Effects of hydroelectric development and fisheries enhancement on spring and summer chinook salmon and steelhead in the Columbia River basin. North American Journal of Fisheries Management 8(1):1–24.

Reid, Scott M., Michael G. Fox, and Thomas H. Whillans. 1999. Influence of turbidity on piscivory in largemouth bass (*Micropterus salmoides*). Can. J. Fish. Aquat. Sci. 56:1362–1369.

Salo, Matthew E., Ernest O. Salo, and Bruce P. Snyder. 1977. A preliminary study of the effects of pier lighting on fishes: Final report, July 1976 to September 1976. FRI-UW-7712. Prepared by University of Washington, College of Fisheries, Fisheries Research Institute, Seattle, for U.S. Department of the Navy.

Savino, Jacqueline F. and Roy A. Stein. 1989. Behavior of fish predators and their prey: Habitat choice between open water and dense vegetation. Environmental Biology of Fishes 24(4)287–293.

Tabor, Roger A. and Wayne A. Wurtsbaugh. 1991. Predation risk and the importance of cover for juvenile rainbow trout in lentic systems. Transactions of the American Fisheries Society 120:728–738.

Thorpe, J.E. 1981. Migration in salmonids, with special reference to juvenile movements in freshwater. in: Proceedings of the Salmon and Trout Migratory Behavior Symposium, first international symposium, June 3–5, 1981. Edited by E.L. Brannon and E.O. Salo. School of Fisheries, University of Washington, Seattle.

Waldman, John R. 1992 (unpublished paper provided by the author). Determining the habitat value of piers and platforms: An empirical approach. 15 pp.

WDNR. 2000. Washington forest practices. Rules – Washington Administrative Code 222, Board Manual; and Forest Practices Act – Revised Code of Washington 76.09. Washington Department of Natural Resources, Forest Practices Division, Olympia, Washington.

Whittier, Thomas R. and Thomas M. Kincaid. 1999. Introduced fish in northeastern USA lakes: Regional extent, dominance, and effect on native species richness. Transactions of the American Fisheries Society 128(5):769–783.

APPENDIX B

Matrix of Data Availability

ECOLOGICAL IMPACTS OF IN-, ON-, AND OVER-WATER STRUCTURES AND ASSOCIATED ACTIVITIES - MATRIX OF DATA AVAILABILITY -													
		In-, On-, and Over-Water Structures										**Associated Activities**	
MECHANISM OF IMPACT	***RESPONSE***	Docks, Piers, & Floats	Marinas	Boat hoists, Boat Lunches, & Boat Ramps	Boathouses	Trash-booms & trash-racks	Work barges	Floating Breakwaters	Log Booms & Log Rafts	Pilings, Wharves, & Dolphins	Riprap & Retaining Walls	Pile Driving & Removal	Construction & Operation
Shore-Zone Habitat Structure Changes	*Predation*												
	Behavior	X	X		X					X	X		
	Habitat Function	X	X		X				X	X	X		
Shading and Ambient Light Changes	*Predation*												X
	Behavior	X											X
	Habitat Function	X								X			
Water Flow Pattern and Energy Disruption	*Predation*												
	Behavior	X								X	X		
	Habitat Function	X								X	X		
Physical-Chemical Disruption (Noise and Water Quality)	*Predation*												
	Behavior											X	X
	Habitat Function	X	X						X		X		X

APPENDIX C

Matrix of Direct Literature Sources

Ecological Impacts of In-, On-, and Over-Water Structures and Associated Activities: Matrix of Direct Literature Sources[a]

Mechanism of Impact & Response	In-, On-, or Over-Water Structure									Associated Activities	
	Docks, Piers, & Floats	Marinas	Boat hoists, Boat launches, & Boat ramps	Boathouses	Trash-booms & Trash-racks	Work Barges	Floating Breakwaters	Log booms & Log rafts	Pilings, Wharves, & Dolphins	Riprap & Retaining Walls	Pile driving & Removal	Construction & Operation
Shore-Zone Habitat Structure Changes												
Predation												
Behavior	[4][5][10][21][26][34][53][54][55][62][65][67][87][89][90][108][121][135]	[19][81]		[9][71]					[62][87][121]	[5][9]		
Habitat Function	[5][9][18][19][22][24][29][50][61][71][81][135]	[19][81]		[9][71]				[84][102][105]	[19][67][135]	[5][9][19][20][61][67][81][103][121]		[40][59][65]
Shading & Ambient Light Changes												
Predation												
Behavior	[53][54][107][120]											[125]
Habitat Function	[19][81][107][135]								[81]			[125][126]
Water Flow Pattern & Energy Disruption												
Predation												
Behavior									[67][87][121]	[67][121]		
Habitat Function	[60][62][73][99][125]								[87][121]	[67][81][121]		
Physical-Chemical Disruption (Noise & Water Quality)												
Predation												
Behavior											[13][14][38]	[11][70][80][81][83][125]
Habitat Function			[19][81]					[84][102][105]		[81]		[19][57][70][77][81][125][126][139]

[a]Numbers in brackets are keyed to entries in the list of references.