Executive Summary: Dredging Activities: Marine Issues

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Characterizing Marine Resource Dredging Effects in Washington State

This paper synthesizes the extent and nature of scientific information about how dredging activities in Washington State potentially affect habitats and key ecological functions supporting recruitment and sustainability of estuarine and marine organisms. A companion paper addresses the same issues in freshwater environments. We present conceptual tools to identify criteria for assessment of potential impacts associated with dredging activities. Identified impacts include: animal injury, behavioral effects, the effects of removing a measured amount of productivity from the landscape, and ecosystem-scale changes due to changes in estuarine circulation. Potential dredging effects are discussed as direct behavioral effects and long-term or cumulative effects. Long-term effects are approached from a landscape ecology perspective with the goal of facilitating the identification of critical regions in a given estuarine or marine landscape area and better identify critical habitat functions and the changes associated with dredging that could affect the realized functions of those habitats

Information pertaining to the disposal of contaminated sediments is provided in a brief overview of disposal mechanisms and decision-making and a bibliography providing access to extensive literature specific to disposal and contaminated sediments.

This paper describes the existing federal and state regulatory framework regulating dredging and disposal activities. Federal and state authorities under the Clean Water Act, the Rivers and Harbors Act of 1899, the Ocean Dumping Act, and applicable state laws are summarized. Prohibited Work Periods (existing and proposed), Hydraulic Code Rules, Habitats of Special Concern, Tidal Reference Areas, and Technical Provisions Applicable to Dredging Activities are also presented.

Dredging Purposes

Marine dredging can be generally characterized as either large-scale "construction" dredging for the creation of new projects or deepening waterways or periodic "maintenance" dredging that serves to maintain existing facilities and sustain existing hydrologic features. Maintenance dredging tends to occur periodically on a regular basis in existing navigation channels in response to the continuous deposition of sediments from freshwater runoff or littoral drift. By far, most dredging in Washington State over the recent past has been maintenance dredging, with few new or expanded projects. Maintenance dredging poses different risks and alterations to marine ecosystems than the nature of those risks posed by new construction.

Including the amount of dredged sediment removed from the Columbia River estuary, annually an average of approximately 5.3 million cubic meters of sediments are dredged from Washington State waterways.

Dredging and Disposal Methods

Dredging methods are divided into two primary categories, hydraulic and mechanical, with each consisting of a variety of equipment types. Dredging methods are selected based upon specific site characteristics such as substrate type, site bathymetry, wave energy, contamination potential, and spatial feasibility.

The physical and chemical nature of the materials dredged determines the disposal methods used. In general, disposal methods include: confined disposal, open-water disposal, and beneficial uses. Dredge materials undergo an extensive evaluation that includes a review of site history for potential contamination and laboratory analysis for the presence of chemicals of concern. If chemicals of concern are identified in site samples, biological testing is then undertaken. Sediments assessed to be unacceptable for open water placement due to contaminant levels being above determined threshold levels, thereby posing risks of unacceptable adverse environmental or human health effects, are typically placed in confined disposal facilities (CDF's). In confined disposal, the dredged material is contained by a diked structure that separates the dredge materials from the water column and the surrounding benthic environments.

When dredged sediments are assessed to be suitable for in-water disposal, both in terms of substrate type and free of contaminant risks, the materials can be used for beneficial purposes above and beyond simple disposal. Beneficial uses include meeting habitat restoration, landfilling, and construction needs. Potential nearshore beneficial uses include: supplementing the beach profile, by adding material to the littoral zone, and beach nourishment, where natural sediment sources and shoreline drift have been impacted. This can decrease nearshore wave heights and reduce damage from erosive waves and storms. Similarly, fish and shellfish habitats that have been historically impacted by dredging or contamination may be rehabilitated or created by the deposition of uncontaminated dredged material.

Beneficial use projects have been most effective, and have provided documented ecological responses, where dredged material sediments are replacing a natural source, and normal shoreline erosion and accretion processes are allowed to operate. However, disposal of dredged material in highly engineered estuarine or nearshore marine features that are atypical for these types of sediments often provide only short-term benefits, require high maintenance, or are sometimes even ecologically counterproductive. Considerable technical thought and evaluation should be required for any beneficial use proposal involving dredged material.

Direct Behavioral Effects

Identified dredging effects can include entrainment of organisms, increased turbidity at the dredging site, fish injury associated with exposure to suspended sediments and decreased dissolved oxygen, and fish behavioral effects due to the effects of noise. Environmental windows are used to constrain dredging and disposal operations to specific periods of operation in order to protect sensitive biological resources and their habitats from detrimental effects. In the identification of direct behavioral effects, this paper presents documented examples of effects identified in entrainment, turbidity, noise, and fish injury field and laboratory studies. Those studies report effects to Dungeness crab, shrimps, salmonids, sturgeon, geoducks, and, in the case of entrainment, to marine fishes such as sculpins, sole, gunnels, prickleback, and smelt. Based on documented life-history strategy similarities shared with those species reported in the above studies, this paper expands the analysis of potential behavioral effects to include a wider range of species using estuarine and marine nearshore habitats.

Entrainment

Entrainment occurs when organisms are trapped during the uptake of sediments and water by dredging machinery. Benthic infauna are particularly vulnerable to being entrained by dredging uptake, but mobile epibenthic and demersal organisms such as burrowing shrimp, crabs, and fish may also be susceptible to entrainment under some conditions.

Turbidity

Turbidity is a natural characteristic of estuarine habitats. It is a product of the receipt of sediments and organic particulates from uplands and freshwater drainages and estuarine and marine primary production levels, combined with the effects of tidal flows, currents, and storms.

Fish Injury

Although juvenile fishes of many species thrive in rivers and estuaries with naturally high concentrations of suspended sediments (SS), studies have shown that the size and shape of suspended sediment and the duration of exposure can be important factors in assessing risks posed to salmonid and other fish populations.

Noise

It has been documented that underwater noise can influence fish behavior. This is likely linked to the importance of sound to fish when they hunt for prey, avoid predators, and engage in social interaction.

Mitigation of Direct Short-Term Behavioral Effects

The site-specific selection of dredging equipment and methods, and operational procedures, can mitigate some of the negative direct effects of dredging. For example: use of a closed or sealed bucket clamshell dredge can be used to minimize the effects of increased turbidity and contain contaminated materials.

Cumulative and Long-term Effects

Long-term effects of dredging include the cumulative effects associated with the dredging or disposal of contaminated materials and the landscape-scale changes in estuarine/marine bathymetry and habitat characteristics resulting from dredging activities. Long-term landscape-scale changes that result from dredging include productivity changes, the conversions of shallow subtidal to deeper subtidal habitats, the conversion of intertidal to subtidal habitats, and changes to estuarine circulation which, through salinity and other changes, can indirectly influence the distribution of estuarine and nearshore marine biota.

Contaminated Sediments and Water

Potential cumulative and long-term effects of dredging include delayed detrimental responses of biota to changes in habitat, water quality, and other conditions that may occur after the actual dredging activity. For instance, contaminant mobilization, contaminant leaching, bioaccumulation, and trophic transfer through the food web can occur during or as a result of the dredging or disposal of contaminated sediments but may not be immediately manifested in exposed biota.

Conversion of Shallow Subtidal to Deeper Subtidal Habitats

Maintenance dredging, by far the most frequent form of dredging in Washington State, converts shallower subtidal habitats to deeper subtidal habitats through periodic deepening to remove accumulated sediments. Depending upon site characteristics, maintenance dredging may occur at varying time intervals. Different dredging timelines likely represent different disturbance regimes both in terms of the ability of the benthos to recolonize prior to redisturbance and the magnitude of benthic productivity affected.

Conversion of Intertidal to Shallow Subtidal Habitats

New construction dredging poses the risk of converting intertidal to subtidal habits. Such conversions are rarely allowed and are only associated with large new construction projects such as marinas. Intertidal conversions pose the risk of impacting plant and animal assemblages uniquely adapted to the particular light, current, and substrate regimes of intertidal areas. The loss of intertidal habitat, given the important rearing and refugia functions that such habitats provide for migrating juvenile salmon and other important fish and shellfish, represent potential reductions in coastal habitat carrying-capacity and connectivity.

Alterations to Estuarine Circulation and Salinity Structure

Estuarine biota is most likely to be subjected to long-term shifts in critical factors such as salinity distribution if dredging significantly changes estuarine bathymetry in regions of sharp salinity gradients (e.g., within the region of salinity intrusion). Effects may be most evident among anadromous and other fishes (e.g. early life history stages) that are particularly sensitive to salinity, especially during transitions from fresh water to saline waters. Deepening an estuarine channel can alter the degree and form of estuarine mixing as the extent of mixing of fresh waters and salt waters in estuaries is dependent, in part, on channel bathymetry, fluvial and tidal energy, substrate roughness, and other lesser factors.

Productivity Changes

For both rural and industrialized urban estuaries, the action of sediment removal and consequently the removal of plants and animals associated with the sediments removes some level of productivity from the system. Such changes alter to some, typically undocumented, degree the habitat structure and ecosystem landscape processes beyond the local influence of the dredge or disposal site. Depending on sediment characteristics, recovery rates have been found to range from within three months, for some benthic macroinvertebrates such as *corophium,* to many years for slow developing macroinvertebrates such as geoducks. In general, consistent long-term productivity, recolonization, and recovery rates are unavailable due to a lack of long-term pre- and post project monitoring to incorporate seasonal and natural variabilities.

Conclusions

Direct Biological Effects

The direct biologic effects of both maintenance and new construction dredging activities include entrainment mortalities, behavioral effects, contaminant release, and noise effects that can induce behavioral change or cause injury and fitness risks. In the case of maintenance dredging, entrainment mortalities and behavioral and noise effects tend to be temporary and localized. The literature reflects that fish gill injury from exposure to high suspended sediment loads is likely the principle mechanism of injury, but to what extent is uncertain and deserves further analysis. Thresholds for gill injury specific to marine and estuarine environments have not been identified. The most relevant issue is likely the ability of fish to volitionally avoid plumes and dredge activity areas. This requires an understanding of the behavioral nature of fish present and the options available to them in order to avoid the dredge areas. We conclude that a clearer understanding of the effects of dredging on a variety of marine fish and shellfish would come from a further synthesis of what is known about their physiology, life-history strategies, water column use, and timing of a wide variety of marine fishes in specific areas. This would enable the development of environmental windows to avoid entrainment and limit risk. We conclude that further identification of injury thresholds and the distribution of species across all life-history stages is required to further assess animal risks.

Based on present data, a turbidity threshold of 200 mg/L in dredging areas would avoid documented juvenile salmonid prey-reaction and predator avoidance changes due to dredge induced turbidity increases. This would also avoid higher levels of turbidity that are known to cause physical injury. This favors the use of the hydraulic cutterhead dredge equipment and requires special precautions, such as no overflow allowance, when dredging in clay and silty substrates. However, this would not necessarily apply if the natural background turbidity at a given site approached or exceeded that threshold, as animals in that area would likely be adapted to high ambient turbidity levels.

Long-Term Effects

The lack of long-term pre- and post project monitoring and documentation of effects of individual dredging projects on the larger ecosystem make it difficult to conclusively identify effects. Conclusive identification of effects is further complicated by the dynamic nature of estuarine and nearshore marine ecosystems and the history of freshwater and marine dredging. The lack of documentation specific to the nature and timing of recolonization preclude the ability to make conclusive statements on long-term effects. Based on what is known about the needs of marine and estuarine biota, we conclude that management of dredging projects and the beneficial use of dredged materials could be an effective tool for protecting and restoring ecosystem functions if projects were planned on an ecosystem landscape scale basis that is specific to the life-history needs of biota utilizing the larger landscape.

Recommendations

Risk Assessment

To improve risk assessment for direct behavioral and long-term ecosystem effects, we recommend: 1) more extensive use of multi-season pre- and post-dredging biological surveys to assess animal community impacts; 2) incorporation of cumulative effects analysis into all dredging project plans; 3) increased use of landscape-scale planning concepts to plan for beneficial use projects most suitable to the area's landscape ecology and biotic community and food web relationships; 4) further identification of turbidity and noise thresholds to assess fish injury risks, and 5) further analysis and synthesis of the state of knowledge on what is known about the spatial and temporal distribution of fish and shellfish spawning, rearing, and migration behaviors. Such an analysis could improve the identification of potential dredging environmental windows and further evaluate the applicability of accepted dredging environmental windows based on best available science.

Dredge Operational Practices

Dredging effects to marine resources can be further minimized through: 1) reducing the volumes of dredged materials removed; 2) reducing the frequency of dredging; 3) avoiding projects that convert intertidal to subtidal habitat; 4) requiring that dredges and barges completely contain dredged material to minimize turbidity increases; 5) employing best management practices to reduce changes to ambient light conditions, and 6) avoiding geoduck losses by avoiding dredging in geoduck tracts. Technological tools such as the "Silent Inspector" should be considered whenever particularly sensitive habitats or organisms are at risk due to dredging proximal to sensitive habitats or in projects where sediments both suitable and unsuitable for unconfined open water disposal will be dredged adjacent to each other.

WHITE PAPER

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

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Overview of Aquatic Habitat Guidelines Project

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

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

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

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

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

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

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

Overview of Marine Dredging White Paper

The primary objectives of this paper include: 1) characterizing the general nature of dredging activities in Washington State; 2) identifying the extent of existing information sources pertaining to those activities; 3) presenting empirically supported evidence and scientific uncertainties concerning the effects marine dredging activities pose to fish and shellfish populations in Washington State; 4) identifying and recommending methods and practices known to decrease negative impacts, and 5) identifying knowledge gaps in need of further exploration to clarify and avoid negative dredging effects to marine ecosystems.

Risks are separated into direct and long-term effects. Direct effects of both maintenance and new construction dredging include animal injury during dredging activities, such as entrainment and burial, and behavioral effects caused by temporarily altered estuarine and marine conditions, such as changes in turbidity and dissolved oxygen. Long-term ecosystem effects include changes in the extent of critical habitat, periodic changes to primary and secondary production (food web effects), and changes in hydrodynamics and sedimentology. This paper is not intended to be an exhaustive literature review on the chemical and biological effects of dredging and disposal. It is an overview of what is known in order to clarify the current state of knowledge pertaining to the risks dredging activities pose to marine habitats and organisms in Washington State. It also provides a separate bibliography on the topic of contaminated sediments.

There is also an extensive body of literature on the chemical and biological effects of dredging and disposal available through the U.S. Army Corp. of Engineers website at http://www.wes.army.mil/el/dots/pubs.html.

Assessment of the State of Knowledge

This literature search reviewed a broad range of existing literature reviews, peer-reviewed journal articles, books, theses/dissertations, and technical reports for information specific to plant and animal species and their interaction with dredging and related effects. The search methodology included interviews with leading experts and resource managers on specific species and ecosystem components, library reviews, and electronic database searches. The electronic database search included the following databases.

Aquatic Sciences and Fisheries Abstracts (ASFA)	http://catalog.lib.washington.edu/search~
UW Fisheries Research Institute Reports (UW-FRI)	http://www.fish.washington.edu/Publications/frireps.html
National Technical Information Service (NTIS)	http://www.ntis.gov/about/index.html
US Army Corps of Engineers (ACOE) database	http://www.wes.army.mil/el/e2d2/index.html
Washington Sea Grant	http://sgpubs.wsg.washington.edu591/wsgpd/FMPro
University of Washington School of Aquatic Fishery Sciences Publications Archives	http://www.fish.washington.edu/Publications/database.html
UW Urban Water Resource Management and Seattle Aquarium Salmon Information Center	http://depts.washington.edu/cuwrm
NOAA-NMFS_ Northwest Fisheries Science Center Publications	http://www.nwfsc.noaa.gov/pubs/
NOAA Regional Library	http://www.wrclib.noaa.gov/lib/
University of Washington library catalog	http://catalog.lib.washington.edu/search~/

The ASFA database has limited on-line membership access but is available to non-members on compact disc in the University of Washington Ocean and Fisheries Library. The ASFA database includes literature dating back to 1982 covering science, technology, and management of marine and freshwater environments. It includes 5,000 international sources in the form of primary journals, source documents, books, monographic series, conference proceedings, and technical research reports. The UW-FRI database includes over 500 reports pertaining to fish and shellfish research conducted by the Fisheries Research Institute (FRI) personnel from 1973 to the present available on the Internet at http://www.fish.washington.edu/Publications/frireps.html. Information pertinent to life history strategies of specific species are also available on-line from WDFW at http://www.wa.gov/wdfw/fish-sh.htm, NOAA Regional Library at, and Northwest Fishery Science Center (NWFSC) at http://research.nwfsc.noaa.gov/pubs/nwfscpubs.html.

Overview of Ecological and Habitat Issues

Defining Estuarine and Marine Habitats

Estuarine and marine plant and animal assemblages are primarily distributed along elevation, salinity, substrate, and wave energy exposure gradients that influence the functional outcome for each species. In recognition of such factors controlling the distribution of species, this paper presents dominant assemblages and habitat characteristics such as wave energy, depth, and substrate of each habitat classification using the Washington Natural Heritage Program Marine and Estuarine Habitat Classification System (Dethier 1990). It also incorporates the basic habitat functions of spawning and rearing and the basic substrate and vegetation characteristics of the Estuarine Habitat Assessment Protocol (Simenstad et al. 1991a) to present a general description of habitat functions. Although other classification systems, such as the Cowardin/National Wetland Inventory System (NWI), are often used to classify habitats, this paper uses the above systems in order to incorporate the variations in dominant species across varying substratum and wave energy regimes. Region-wide use of the above classification systems provide a consistent statewide framework for existing data and future inventory work and enable reasonable predictability as to the presence of dominant plant and animal species in a given habitat (Dethier 1990; Simenstad et al. 1991a). Table 1 provides definitions of intertidal and subtidal ecosystems using both the NOAA tidal datum and the Dethier classification systems. Table 2 defines tital levels whereas Figure 1 defines MLLW or 0.0 tides by the average of lower low tides. See Appendix A for definitions of the terms used in the Dethier system and the plant and animal species associated with particular habitat subsystem classifications.

Table 1. Intertidal Definitions.

Intertidal Ecosystems	Depth Classifications	NOAA Tidal Datum Classifications
Habitats affected only by higher tides, may not often be wet except from spray or rain	Supralittoral Backshore	▪ Above MHWS ▪ In the San Juan Archipelago, the lower limit is 2.1 m (7 ft) above MLLW (0). ▪ In Puget Sound, the lower limit is about 2.7 m (9 ft) above MLLW. This includes a range from 3m (14 ft) in Olympia to 2m (7 ft) in Port Angeles
Habitats regularly inundated and uncovered by the tides	Eulittoral or intertidal	▪ Between MHWS and MLLW
Habitats rarely, if ever, completely uncovered by low tides	Shallow subtidal	▪ 15 meters or less below MLLW
Habitats always submerged	Deep subtidal	▪ >15 meters below MLLW

Adapted from Dethier (1990), NOAA (2001), and Kozloff (1983)

Table 2. Defining Tidal Levels.

▪ MHWS = Mean High Water Springs	Average height of the high waters of the spring tides. Spring tides have increased range or tidal currents of due to the moon being full or new.
▪ MHHW = Mean Higher High Water	Average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch.
▪ MHW = Mean High Water	Average of all the high water heights observed over the National Tidal Datum Epoch.
▪ MLW = Mean Low Water	Average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch.
▪ MLLW = Mean Lower Low Water	Average of all the low water heights observed over the National Tidal Datum Epoch.

(NOAA 2001)

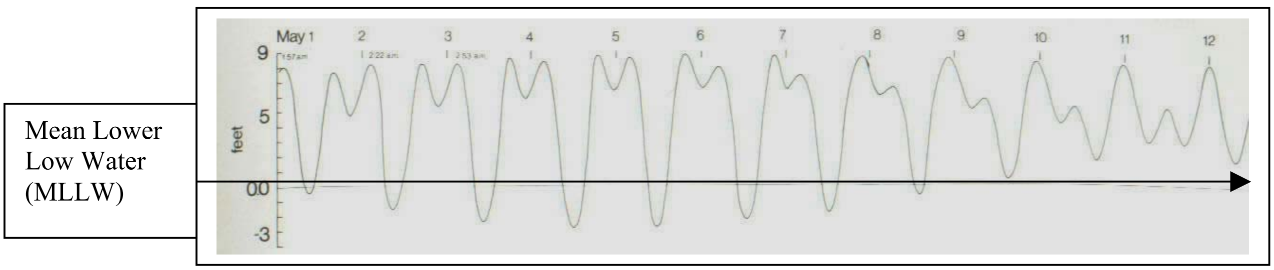

Figure 1. Defining MLLW or 0.0 Tides by the Average of Lower Low Tides
(Source: Kozloff 1983)

This paper describes fish assemblages by their intertidal and subtidal habitat residency patterns. For this purpose, fish assemblages are categorized as **resident, seasonal resident, migratory, or transient species**. This paper categorizes estuarine and marine habitat functions under the general functions of juvenile rearing, spawning, or adult residency. Figure 2 depicts the distribution of nearshore habitats along tidal elevations and some of the assemblages of plants and animals that are typically found in those habitats in the Pacific Northwest (Krukeberg 1991). Table 3 is a general representation of the use of those habitats by resident, seasonal resident, migratory and transient fishes. This paper also describes animal distribution and use of the water column for the functions of juvenile rearing, reproducing or adult residency.

Shallow Subtidal and Intertidal Habitats

In general, variations in the densities of fishes and macroinvertebrates correlate to seasonal variations in vegetative cover and wave exposure (e.g. wave and current energy) in combination with the varying life-history needs of particular species that determine the spatial and temporal extent of their habitat use. Species dependent upon these nearshore habitats have developed complex life history strategies utilizing seasonally available refugia and resources (Shaffer 1995; Carr 1989; Love et al. 1991).

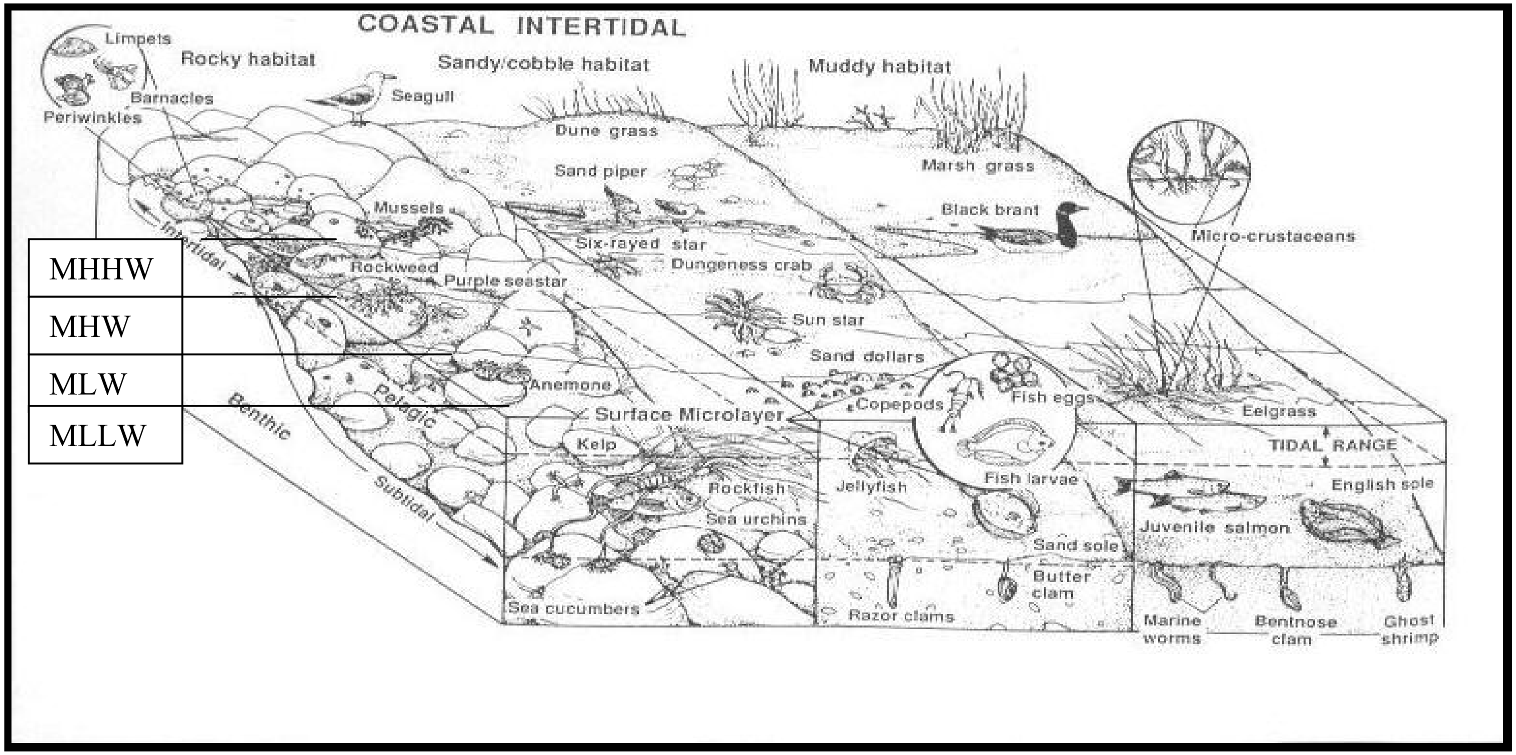

Figure 2. Nearshore Habitats and Tidal Elevations

(adapted from Krukeberg 1990, artist Sandra Noel)

Table 3. Fish Use of Nearshore Habitat Types

	Rocky Kelp	Rocky Cobble	Shallow Exposed Gravel-Cobble	Sand-Gravel	Mud/Sand Eelgrass
MHHW +4 meters	Rearing: Resident & transient fishes	Rearing: Resident fishes	Rearing: Resident fishes	Spawning: Transient Rearing: Transient fishes	Rearing: Resident, transient & migratory fishes
MHW +2 meters	Rearing: Resident & transient fishes	Rearing: Resident, juvenile migratory & transient fishes	Rearing: Resident, juvenile migratory & transient fishes	Spawning: Transient fishes	Rearing: Resident, transient & migratory fishes
MLW +1 meter	Rearing: Resident & transient fishes	Rearing: Resident juvenile migratory & transient fishes	Rearing: Resident, juvenile migratory & transient fishes	Spawning: Transient fishes	Rearing: Resident, transient & migratory fishes
MLLW 0.0 and below	Spawning: Transient fishes Rearing: Resident & transient fishes	Rearing: Migratory & transient fishes	Rearing: Resident & transient fishes	Spawning: Transient fishes	Spawning: Transient fishes Rearing: Resident, migratory, & transient fishes

In early spring, increased sunlight and vegetative growth correlate with increased abundances of larval and juvenile fish taking advantage of the abundant nearshore prey resources and refugia associated with vegetation. Each habitat possesses distinctive fish and macroinvertebrate species adapted to the physical characteristics and the associated flora and fauna of that habitat. Fish densities in particular habitats are seasonally dependent. For example, high densities are found in rock/kelp habitat in spring and declining fish densities are found in fall and winter (Miller et al. 1976). Seasonal fluctuations in wave and low tide exposure can result in some habitats, such as shallow cobble habitats, being more physically stressed than other, more protected habitats (Miller et al. 1976). Similarly, Miller et al (1976) found rockfish (*Sebastes* spp.) and Pacific tomcod (*Microgadus proximus*) to migrate out of such habitats in fall and early winter with populations of kelp greenling, sculpins, perches, and tubesnouts becoming more prominent in the winter. Table 3 classifies fish habitats as rocky-kelp, rocky- cobble, shallow exposed gravel-cobble, sand-eelgrass (*Zostera marina*), and mud-eelgrass habitats. These classifications are consistent with the nearshore food web and fish community studies of Miller et al. (1976) and Simenstad et al. (1979) that documented fish habitat associations based upon scientific inventorying and analysis. The following habitat descriptions are a very general and simplified characterization of nearshore habitat types. These habitat characteristics are found to vary significantly depending upon specific geomorphologic and wave energy characteristics along with seasonal variations in prey resources specific to a given region (Miller et al. 1976; Simenstad et al. 1979; Cross 1981).

Rocky-kelp Habitats

Rocky-kelp habitats are predominantly subtidal habitats except in northern Puget Sound. These habitats are characterized by well-flushed steep gradients. Although these habitats are generally not as capable of supporting the large numbers of infaunal species found in soft-sediment environments, epibenthic and epiphytal shrimps, crabs, mysids, gammarid amphipods, isopods, and copepods are able to occupy the kelp holdfast and macroalgae understory microhabitats. The food web organized around this environment supports bottomfish that feed on these organisms. These bottom or demersal fishes, in turn, support harbor seals, larger demersal fishes, sea lions, and Orcas (Simenstad et al.1979).

Rocky-cobble Habitats

Rocky-cobble habitats include exposed intertidal rocky and cobble habitats, seaweed, and the extensive beneath-rock habitat provided by intertidal cobble beaches. In the intertidal rocky kelp habitat, detritus production is sustained by the senescence of annual macroalgae and herbivores such as chitons, limpets, sea urchins, and snails that graze and release macroalgae from the substrate (Simenstad et al. 1979). Seasonal fluctuations are prominent in this habitat; particularly those associated with the annual die-off macroalgae and the massive recruitment of barnacles and mussels.

Shallow Exposed Gravel-cobble Habitats

Shallow exposed gravel-cobble habitats at intertidal depths are characterized by exposure to wave action. This environment largely restricts the presence of macroalgae or eelgrass and results in a less diverse food web structure. Detritus is transported and accumulated in unconsolidated sediments which serve to bind the detritus and enable its utilization by detritus grazing epibenthic crustaceans, such as gammarid amphipods, cumaceans, harpacticoid copepods, mysids, and isopods supporting fishes, birds and marine mammals (Simenstad et al.1979).

Sand-eelgrass Habitats

Sand-eelgrass habitats are typically protected habitats characterized by shallow, semi-enclosed embayments with low to moderate energy beaches. These environments allow for the accumulation and stabilization of sand, mixed fine gravels, and the colonization of eelgrass. The stable substrates of the protected environment provide rich benthic infaunal and epibenthic communities and provide prey resources for juvenile fishes seeking protection in the eelgrass beds. The eelgrass shoots serve to increase the substrate available for epiphytic algae and associated fauna. They also reduce wave and current action, trap sediments and detritus, and maintain high dissolved oxygen concentrations through photosynthetic activity. Through shading at low tides, the eelgrass also minimizes temperature fluctuations that would otherwise occur with direct sunlight. The detritus resulting from eelgrass dieback provides carbon energy directly to important detritivores such as harpacticoid copepods, gammarid amphipods, and isopods and indirectly to those carnivores preying on benthic organisms (Simenstad et al. 1979).

Mud-eelgrass Habitats

Mud-eelgrass habitats are characterized by fine mud and sand-mud substrates in protected areas. They are most expansive in estuarine mudflat habitats. Epibenthic crustaceans have been found to be much denser in these habitats than in the sand eelgrass habitat by as much as five times. This could be due to the ability of fine substrates to entrain organic matter input from vascular salt marsh plants that are transported into the estuary by way of spring runoff and spring tides (Simenstad et al. 1979).

Marine riparian Habitats

Marine riparian habitats in the upland areas above MHHW along the shoreline provide some of the same functions that freshwater riparian areas provide (Desbonnet et al. 1995) as well as additional functions unique to nearshore systems (Brennan and Culverwell, In prep; Cedarholm 2000; Gonor et al. 1988). Marine riparian areas upland of the MHHW line can serve to stabilize beaches and help build berms and backshore areas. Other functional contributions of marine riparian habitats include bank stabilization, water quality protection; microclimate temperature regulation, precipitation and moisture retention, and nutrient and prey input from overhanging vegetation. The large woody debris (LWD) input from these riparian areas also provides roosting, nesting, foraging, and spawning substrate for both invertebrates and plants (Brennan and Culverwell, in Prep).

Deep Subtidal Habitats

Rock and Boulders: High Energy, Deep Habitats

Rock and boulders: high energy, deep habitats are characterized by depths of over 15 meters with fairly high currents. These habitats are dominated by encrusting invertebrates with few types of kelp relative to shallower areas. Giant white anemone are characteristic of these habitats encrusting coralline algae, red algae, red, white, and green urchins, brachiopods, polycheates, cucumbers, corals, scallops, barnacles, sea stars, hydrocoral, anemones, bryozoans and hydroids, basket stars, and ascidians. The fishes include rockfish, lingcod, gobies, and sculpins.

Rock and Boulders: Low Energy, Deep Habitats

Rock and boulders: low energy, deep habitats are characterized by sponges, barnacles, polycheates, galatheid crab. Anemone, coral, sea cucumbers, ascidians and sea stars are also common to these habitats. The fish include longfin sculpin, gobies, and widow, quillback, and copper rockfish.

Subtidal Cobble: High Energy, Deep Habitats

Subtidal cobble: high energy, deep habitats are characterized by scoured substratum. Horse mussel, giant barnacles, serpulid worms, urchins, rock scallop fan worms, hydroids, ophiuroids, basket star, anemones, crab (*Lophopanopeus bellus)*, and clams are common to these habitats.

Mixed-Coarse: Moderate to High Energy, Deep Habitats

Mixed-coarse: moderate to high energy, deep habitats are characterized by mussels and barnacles. On the outer coast, bivalves, gastropods, polychaetes, seastars, and Octopus dominate assemblages with abundances of shrimp.

Mixed-Fines: High Energy, Deep Habitats

Mixed-fines: high energy, deep habitats are characterized by bivalves, a variety of amphipods, snails, and polychaetes.

Mixed-Fines: Moderate to Low Energy, Deep Habitats

Mixed-fines: moderate to low energy, deep habitats are characterized by burrowing anemones, sea pens, nudibranchs, aseroids, polychaetes, hydroids, bivalves, scaphopods, sea cucumbers, crab (*Cancer magister* and *Pugettia* spp.*)*, seastars, cephalopods, and sea pens. Geoducks may also occur in patches. Fish include rocksole, ratfish, dogfish, and tomcod, sanddabs, C-O sole, snake prickleback, tomcod, and dogfish.

Mud: Low Energy, Deep Habitats

Mud: low energy, deep habitats are characterized by cephlopods, bivalves, sea cucumbers, small snails, sea whips, anemones, the nudibranchs, polychaetes, nematodes, chaetopterids, and starfish Fish include hagfish (outer coast), ratfish, lemon sole, sculpins, blackbelly eelpout and others common to eelgrass.

Deep Subtidal Sand and Mud Channels

Deep subtidal sand and mud channels are characterized by a variety of polychaetes, numerous spioinds, a variety of amphipods, crab (*Cancer magister)*, and shrimp (*crangon* spp.*).* Fishes include shiner perch, peamouth, Pacific tomcod, snake prickleback, sculpins, speckled sanddab, English sole, starry flounder, and juvenile salmon. These are extremely rich and important habitats for diverse bird and fish assemblages. Wading and surface-foraging birds use the channel edges, surface and diving birds such as grebes, cormorants, mergansers, scoters, waterfowl, auklets and murrelets feed and roost along these channels. Kingfishers, osprey, eagles, terns, and others dive for the fish. Racoon, beaver, nutria, rover otter, and marine mammals also feed in these channels.

Fish Habitat Use

Resident and Seasonal Resident Fishes

For the purposes of this paper, fishes are classified by their behavior relative to the extent of their utilization of such environments. These classifications are **resident, seasonal resident, migratory and transient fishes. Resident** and **seasonal resident fishes** appear to share particular similarities in the extent of their dependency upon shallow water habitats compared to those species classified as migratory or transient**. Resident fishes** remain in intertidal habitats throughout their various life-history stages with some species, such as the saddleback gunnel and sculpins, remaining in the intertidal area throughout even the daily tidal cycles. In contrast, the **seasonal residents**, such as Pacific herring, Pacific cod, walleye pollock, lingcod, and English sole reside in nearshore intertidal and subtidal habitats only seasonally with their intertidal residency often associated with specific life history stages (e.g., juvenile rearing or spawning). Although Pacific herring share many similarities with sand lance and surf smelt such as spawning in shallow subtidal and intertidal areas, studies suggest differences in their use of shallow nearshore habitats that likely set them apart from sand lance and surf smelt in their connection with the shallow nearshore habitats. Simenstad et al. (1979) consistently found post larval and juvenile herring in nearshore habitats but not after those young stages. In contrast, sand lance and surf smelt were found to periodically use the shallow nearshore habitats throughout various life history stages. Herring diets have been found to vary both with season and habitat with the diet of very young juveniles found to be composed of shallow sublittoral epibenthic organisms, such as the harpacticoid copepod, by as much as 82% (Simenstad et al. 1979). For these reasons, this report classifies herring as **seasonal resident fish**. For all of these intertidal residents, available refuge often determines their low tide distribution, feeding, recruitment, and colonization functions (Williams, 1994; Gibson 1982; Mayr and Berger 1992).

Table 4 associates those fishes always residing in the eulittoral and shallow subtidal zones with the general habitats they use and Table 5 identifies their vertical distribution. This is a representative list of such fishes and is not an exhaustive list of intertidal fishes in Washington State marine waters. An exhaustive list would include over 200 species. Tables 6 and 7 list a representation of priority fishes characterized as **seasonal residents** of these nearshore zones. Table 8 lists those fish classified as **migratory fishes** utilizing the nearshore zone, which are the salmonids characteristic of this region. Tables 9 and 10 list examples and habitat uses of priority species classified for the purposes of this paper as **transient fishes**. These tables also include a general description of life-history stages and annual timing of their use of these nearshore habitats.

Table 4. Resident Fishes - Habitat Use

Intertidal Resident Fishes			Habitat Use				
Family	Scientific name	Common Name	Rocky Kelp	Rocky & Cobble	Shallow Exposed Gravel-Cobble	Sand Eelgrass	Mud Eelgrass
Gobiesocidae	*Gobiesox maeandricus*	Northern clingfish		●			
Stichaeidae	*Anoplarchus purpurescens*	High cockscomb		●			
	Xiphister atropupureus	Black prickleback		●			
	Phytichthys chirus	Ribbon prickleback		●			
	Xiphister mucosus	Rock prickleback		●			
	Lumpenus sagitta	Snake prickleback			●	●	●
Pholidae	*Apodichthys flavidus*	Penpoint gunnel	●	●		●	●
	Pholis laeta	Crescent gunnel	●	●		●	●
Hexagrammidae	*Hexagrammos decagrammus*	Kelp greenling	●				
Syngnathidae	*Syngnathus leptorhynchus*	Bay pipefish				●	●
Cottidae	*Jordania zonope*	Longfin sculpin	●				
	Artedius fenestralis	Padded sculpin			●		●
	Ascelichthys rhodorus	Rosylip sculpin		●			
	Artedius lateralis	Smoothhead sculpin		●			
	Clinocottus acuticeps	Sharpnose sculpin		●			●
	Blepsias cirrhosus	Silverspotted sculpin			●	●	●
	Enophrys bison	Buffalo sculpin			●	●	●
	Leptocottus armatus	Pac. staghorn sculpin			●		
	Clinocottus embryum	Calico sculpin		●		●	●
	Clinocottus globiceps	Mosshead sculpin		●			
	Oligocottus maculosusu	Tidepool sculpin		●	●		●
	Artedius harringtoni	Scalyhead sculpin	●				
	Oligocottus snyderi	Fluffy sculpin		●			
Embiotocidea	*Cymatogaster aggregata*	Shiner perch			●	●	●
	Rhacochilus vacca	Pile perch				●	
Cyclopteridae	*Liparis florae*	Tidepool snailfish			●		
Gasterosteidae	*Aurlorhynchus flavidus*	Tube-snout		●		●	
Bothidae	*Citharichthys stigmaeus*	Speckled sanddab				●	

Adapted from Cross 1982 and Simenstad et al. 1979

Table 5. Resident Fishes - Water Column Use

Intertidal Resident Fishes			Water Column Distribution			
Family	Scientific Name	Common Name	Spawning Habitat	Eggs	Larvae	Adult Habitat
Gobiesocidae	*Gobiesox maeandricus*	Northern clingfish	Demersal	Demersal	Pelagic	Demersal-rock
Stichaeidae	*Anoplarchus purpurescens*	High cockscomb	Demersal	Demersal	Pelagic	Demersal
	Xiphister atropupureus	Black prickleback	Demersal: rock	Demersal	Pelagic	Demersal intertidal
	Phytichthys chirus	Ribbon prickleback	Unk	Unk	Unk	Demersal
	Xiphister mucosus	Rock prickleback	Demersal	Demersal	Pelagic	Demersal
	Lumpenus sagitta	Snake prickleback	Unk	Unk	Unk	Demersal
Pholidae	*Apodichthys flavidus*	Penpoint gunnel	Demersal	Demersal	Pelagic	Demersal
	Pholis laeta	Crescent gunnel	Demersal	Demersal	Pelagic	Demersal
Hexagrammidae	*Hexagrammos decagrammus*	Kelp greenling	Demersal: rocky	Demersal	Pelagic	Demersal
Syngnathidae	*Syngnathus leptorhynchus*	Bay pipefish	Unk	Unk	Unk	Inshore protected areas
Cottidae	*Jordania zonope*	Longfin sculpin	Unk	Demersal	Unk	Demersal
	Artedius fenestralis	Padded sculpin	Demersal: rocks	Demersal	Pelagic	Demersal
	Ascelichthys rhodorus	Rosylip sculpin	Unk	Unk	Unk	Demersal
	Artedius lateralis	Smoothhead sculpin	Demersal	Demersal	Pelagic	Demersal
	Clinocottus acuticeps	Sharpnose sculpin	Unk	Demersal	Pelagic	Demersal
	Blepsias cirrhosus	Silverspotted sculpin	Demersal	Demersal	Pelagic	Demersal
	Enophrys bison	Buffalo sculpin	Demersal	Demersal	Pelagic	Demersal
	Leptocottus armatus	Pac. staghorn sculpin	Unk	Demersal	Pelagic	Demersal
	Clinocottus embryum	Calico sculpin	Unk	Unk	Unk	Demersal
	Clinocottus globiceps	Mosshead sculpin	Unk	Unk	Unk	Demersal
	Oligocottus maculosusu	Tidepool sculpin	Demersal	Demersal	Pelagic	Demersal intertidal
	Artedius harringtoni	Scalyhead sculpin	Unk	Unk	Pelagic	Demersal
	Oligocottus snyderi	Fluffy sculpin	Unk	Unk	Unk	Demersal
Embiotocidea	*Cymatogaster aggregata*	Shiner perch	Pelagic nearshore			Pelagic nearshore
	Rhacochilus vacca	Pile perch	Pelagic			Pelagic
Cyclopteridae	*Liparis florae*	Tidepool snailfish	Unk	Unk	Unk	Demersal
Gasterosteidae	*Aurlorhynchus flavidus*	Tube-snout	Demersal	Demersal	Pelagic	Pelagic nearshore
Bothidae	*Citharichthys stigmaeus*	Speckled sanddab	Unk	Unk	Pelagic	Demersal

Adapted from Garrison and Miller 1982

Table 6 Seasonal Resident Fishes - Habit Use

Seasonal Resident Fishes			Habitat Use				
Family	Scientific Name	Common Name	Spawn	Juvenile Rearing	Adult Res.	Habitat Type	Timing
Clupeidae	*Clupea harengus pallasi*	Pacific herring	●	●	●	1) Protected sand-gravel eelgrass shallow subtidal 2) Mud eelgrass 3) Subtidal 4) Rocky/cobble/kelp	Juvenile: Year-round Adult: Winter-early spring
Gadidae	*Gadus macrocephalus*	Pacific cod		●		1) Enclosed 2) Sand-eelgrass 3) Cobble 4) Gravel	Summer–Fall
	Theragra Chalcogramma	Walleye pollock		●		1) Shallow exposed gravel-cobble 2) Mud eelgrass 3) Sand eelgrass	Juvenile: Spring–Winter
Hexagrammidae	*Ophiodon elongatus*	lingcod		●		Juvenile: 1) gravel 2) mud eelgrass Adult: Subtidal rocky/kelp	Juvenile: Summer Adult: Year-round
Pleuronectidae	*Pleuronectes vetulus*	English sole		●	●	1) Shallow exposed gravel-cobble 2) Mud eelgrass 3) Sand eelgrass	Year-round Juvenile recruitment Jan–Feb and April–May on coast and Dec–March and May to July in Puget Sound

● Indicates extensive use

Adapted from Garrison and Miller 1982; Miller et al. 1976; Shi 1987; Simenstad et al. 1979

Table 7 Seasonal Resident Fishes - Water Column Use

Seasonal Resident Fishes			Water Column Distribution			
Family	Scientific Name	Common Name	Spawning Habitat	Eggs	Larvae	Adult Habitat
Clupeidae	*Clupea harenus pallasi*	Pacific herring	demersal	demersal	pelagic	pelagic
Gadidae	*Gadus macrocephalus*	Pacific cod	semi-demersal	demersal	pelagic	semi-demersal
	Theragra Chalcogramma	Walleye pollock	pelagic	pelagic	pelagic	demersal or pelagic
Hexagrammidae	*Ophiodon elongatus*	lingcod	demersal on rocks & rocky crevices	demersal	pelagic	demersal: rock & algae
Pleuronectidae	*Pleuronectes vetulus*	English sole	demersal	pelagic	pelagic	demersal: moderate depths

Adapted from Garrison and Miller 1982; Matthews 1987

Table 8. Migratory Fishes - Habitat Use

Migratory Fishes			Nearshore Estuarine Habitat Use			
Family	Scientific Name	Common Name	Adult	Juvenile Rearing & Size	Preferred Habitat Types	Timing
Salmonidae	*Oncorhynchus keta*	Chum		● 30-50mm	1) enclosed 2) channel/slough	Feb–June
	Oncorhynchus gorbuscha	Pink		● 33-40mm	1) enclosed 2) channel/slough	Feb–June (even yrs.)
	Oncorhynchus tshawytscha	Chinook		● 30-120mm	1) enclosed 2) channel/slough	Feb–mid-Sept
	Oncorhynchus kisutch	Coho		●	1) open	March–August
	Oncorhynchus nerka	Sockeye		●	1) open	Early June
	Oncorhynchus clarki clarki	Coastal cutthroat	X	●	1) open	Year round (as smolts, sub-adults, and adults)
	Oncorhynchus mykiss	Steelhead	[illegible]	[illegible]	1) open 2) deep	March–June with outmigration March–May
	Salvelinus confluentus	Bull trout	[illegible]	[illegible]	1) shallow nearshore	Year round (as smolts, sub-adults, and adults). Dec–Feb freshwater overwintering.
Acipeneridae	*Acipenser transmontanus*	White sturgeon	[illegible]	[illegible] sh		Adults: Late winter-spring; Subadults: Summer
	Avcipenser medirostris	Green sturgeon	[illegible]	[illegible]		

● Indicates extensive use

Table 9. Transient Fishes - Habitat Use

Transient Fishes			Nearshore Habitat Use				
Family	Scientific Name	Common Name	Spawn	Juvenile Rearing	Adult Res.	Habitat Type	Timing
Osmeridae	*Hypomesus pretiousus*	Surf smelt	●	●	●	1) Protected sand-gravel eelgrass shallow subtidal 2) Mud eelgrass 3) Subtidal 4) Rocky/kelp-adults & larvae only	Juvenile: Spring–summer, suspected year-round Adults: Year- round. Spawning is continuous throughout the year in Puget Sound.
Ammodytidae	*Ammodytes hexapterus*	Pacific sand lance	●	●	●	1) Protected sand-gravel eelgrass shallow subtidal 2) Mud eelgrass 3) Subtidal 4) Rocky/kelp	Juvenile: spring-summer. Larvae in plankton Jan–April Adults: Year- round
Scorpaenidae	*Sebastes (spp.)*	Rockfish		●		Juvenile: 1) Shallow gravel 2) Shallow subtidal sand eelgrass Adult: 1) Subtidal rocky/kelp 2) Bravel	Juvenile: Spring-summer Adults: Year- round

● Indicates extensive use — Adapted from Matthews 1989, 1990; Miller et al. 1976; Simenstad et al. 1979; Penttila 2000,b,c; 2001

Table 10. Transient Fishes - Water Column Use

Transient Fishes			Water Column Distribution			
Family	Scientific Name	Common Name	Spawning Habitat	Eggs	Larvae	Adult Habitat
Osmeridae	*Hypomesus pretiousus*	Surf smelt	Demersal	Demersal	Pelagic	Pelagic
Ammodytidae	*Ammodytes hexapterus*	Pacific sand lance	Demersal on sand	Demersal	Pelagic	Pelagic/demersal-burrowing (diurnal cycle)
Scorpaenidae	*Sebastes (spp.)*	Rockfish			Pelagic juveniles	Semi-demersal

Adapted from Garrison and Miller 1982

Pacific Herring (*Clupea harenus pallasi*)

Pacific herring *(Clupea harenus pallasi)* the predominant species in Northern Puget Sound's neritic fish assemblages (Fresh 1979), typically utilize vegetated nearshore habitats for spawning and juvenile rearing. Although there is variation region-wide in spawning times specific to particular beaches, Pacific herring generally spawn in late winter and early spring from January through early April. Typically females deposit eggs on nearshore vegetation, such as kelp, eelgrass, and marine algae between the mean higher high tide line (MHHW) and out to depths of -40 feet below (MLLW) (Penttila 2000b). However, in Grays Harbor and Willapa Bay, some populations spawn on the outer edges of the natural low salt marshes (predominantly *Salicornia, Fucus* and *Ulva)* or on over-wintering *Spartina* stubble, rather higher in the intertidal zone than herring spawn is customarily found on Puget Sound shorelines (Penttila 2001). The viability of these spawns is compromised by atmospheric exposure during low tide. Some stocks are thought to migrate annually from inshore spawning grounds, such as Puget Sound, to open ocean feedings areas. Studies in Northern Puget Sound (Simenstad et al. 1979) have found juvenile Pacific herring to be feeding principally on epibenthic organisms, with harpacticoid copepods comprising 82% of their diet. Pacific herring are an important prey item for many marine organisms. Pacific herring have been found to comprise the following diet percentages of specific fish species: Pacific cod (42%), walleye pollock (32%), lingcod (71%), Pacific halibut (53%), coho and chinook salmon (58%) (Environment Canada 1994). All documented herring spawning sites in Washington State are afforded "no net loss" regulatory protection during the application of the Washington Administrative Code (WAC) Hydraulic Code Rules.

Pacific Cod (*Gadus macrocephalus*)

Pacific cod *(Gadus macrocephalus)* are found throughout Washington's inside marine waters. Juvenile cod (Miller and Borton 1980) settle to shallow vegetated habitats, such as sand-eelgrass, in late summer where they find shelter and rich abundances of prey resources in the form of copepods, amphipods, and mysids (Matthews 1987). Adult Pacific cod live near the bottom over soft sediments. They feed on Pacific sand lance, Pacific herring, walleye pollock, sculpins, flatfishes, and invertebrates, such as euphausids, crabs, and shrimp (Albers and Anderson 1985; Jewett 1978; Blackburn 1986; and Westrheim and Harling 1983). Following sinter spawning, they migrate to feed in deeper, cooler waters. In Puget Sound, Pacific cod have been found to concentrate in shallow embayments such as Port Townsend Bay and Agate Passage but disperse to deeper waters during the remainder of the year (Walters 1984; Bargmann 1980). For example, Walters (1984) found that following winter hatching, Pacific cod in Port Townsend Bay showed a tendency to remain in the shallow areas until June. Westrheim (1982) distinguished four Pacific cod stocks in the inland marine waters of British Columbia that included three resident stocks and one highly migratory stock with migration and straying occurring between British Columbia and Washington waters. Stomach content analyses have demonstrated that Pacific herring are the main prey items of Pacific cod (Palsson 1990). Water temperature and the presence or absence of Pacific herring has been found to affect Pacific cod recruitment and abundance in British Columbia (Palsson 1990). Walters et al. (1986) found that when Pacific herring abundances are low, cod are likely to move to other feeding grounds or suffer from reduced egg production due to the lack of prey resources.

Pacific Hake (*Merluccius productus*) and Walleye Pollock (*Theragra chalcogramma*)

Pacific hake *(Merluccius productus)* and walleye pollock (*Theragra chalcogramma)* are midwater, cold-water schooling fishes that undergo northward feeding migrations in the summer and return to southerly waters for winter spawning (West 1997). As juveniles, they migrate to inshore, shallow habitats for their first year and move back to deeper waters in their second year. Walleye pollock juveniles are semi-demersal and are very adaptable to a variety of substrate types (Matthews 1987). As adults, both Pacific hake and walleye pollock are midwater schooling codfishes with the Pacific hake population migrating from California and Baja in the summer to feed in Washington and British Columbia (West 1997). Simenstad (1979) and Walters (1984) found juvenile walleye pollock to eat mysids, calanoid and harpacticoid copepods, gammarid amphipods, and juvenile shrimp. A small, genetically distinct, resident population in northern Puget Sound migrates seasonally between Port Susan and Saratoga Passage that has experienced a severe decline in recent years (West 1997).

Lingcod (*Ophiodon elongatus*)

Lingcod *(Ophiodon elongatus)* typically have a relatively small home range. They spawn between December and March, laying eggs in rocky crevices in shallow areas with strong water motion. Eggs are then fertilized and vigorously defended by the males. After dispersing from their nests, larvae spend two months in pelagic habitats as surface-oriented larvae. From late spring to early summer, juveniles move to benthic habitats, settling in shallow vegetated habitats (Buckley et al. 1984; Cass et al. 1990; West 1997). It is likely that juveniles use nearshore habitats for both refuge and feeding. In their first fall season, juveniles move to flat shoals and other uncomplex, bottoms where they will spend a year or two growing to a size large enough to avoid predation by other reef-dwelling species (i.e. rockfish, cabezon, larger lingcod). They will then move to their adult rocky reef habitat.

English sole (*Pleuronectes vetulus*)

English sole *(Pleuronectes vetulus)***,** a common offshore species and the most abundant flatfish in Puget Sound, utilizes a variety of nearshore habitats as juveniles. Miller et al (1976) found juveniles in gravel, sand-eelgrass, and mud-eelgrass habitats. Larvae were found in nearshore habitats between March and May and juveniles were found throughout the year in eelgrass habitats feeding on annelids. English sole spawn offshore along the coast between September and April (Kruse and Tyler 1983). Garrison and Miller (1982) report that English sole in Puget Sound are in spawning condition from at least January to April with most spawning occurring between February and March (Smith 1936). Shi (1987) reports two recruitment peaks for juveniles with one occurring in January-February and another in April-May. Two influxes of juveniles have also been observed in Puget Sound, one in winter (December - March) and one in summer (May - July). Following a pelagic early larval stage, they move into the benthos of coastal and estuarine areas where they assume a demersal existence for the remainder of their lives (Tasto 1983; Stevens and Armstrong 1984; Krygier and Pearcy 1986; Boehlert and Mundy 1988). English sole larvae of 15mm total length (TL) settle to the substrate and at times burrow into it. Gunderson et al. (1990) found that as fish reached 55mm in length, the majority was found in estuarine waters with migration from the estuaries beginning at 75-80 mm TL. Shi (1987) found that as fish reached 100 mm TL they migrated out of estuaries and into open coastal areas. Similarly, Gunderson et al. (1990) found fish greater than 125 mm TL to have migrated from the estuaries with the migration in and out of estuaries to be length-dependent. The estuaries provide juveniles with prey resources and refuge. The disproportionately high settlement in estuaries and larval distribution patterns suggest an active migration or directed transport to estuarine areas for settlement (Reilly 1983; Boehlert and Mundy 1988; Jamieson et al. 1989). These findings are consistent with a wide variety of fish and crustacean studies demonstrating the importance of specific larval behavior patterns and interactions with physical processes that ensure recruitment in estuaries (Gunderson et al. 1990; Rothlisberg 1982; Rothlisberg et al. 1983; Epifano et al. 1984; Johnson, D.R. et al. 1984; Sulkin and Epifano et al 1986; Boehlert and Mundy 1988; Epifanio 1988; Shenker 1988). Gunderson et al (1990) states that clearly prey availability is of major significance in evaluating the advantages of an estuarine existence. In studies off the Oregon Coast, English sole 17-35 mm TL fed primarily on polychaete palps, juvenile bivalves, and harpacticoid copepods. Juveniles 35-82 mm TL fed on the larger amphipods and cumaceans (Hogue and Carey 1982). Toole (1980) found English sole, less than 50 mm TL, to feed almost exclusively on harpacticoid copepods and the diets of 66-102 mm TL sole to be dominated by polychaetes. Similarly, Buechner et al (1981) found the diets of English sole in Grays Harbor to be dominated by harpacticoid copepods and gammarid amphipods from April and August and polychaetes predominating in October.

Migratory Fishes

These species utilize nearshore habitats as they continue along their migratory corridor to their adult habitats. Their adult habitats are primarily not in nearshore areas. Juvenile salmonids are examples of migratory fish that utilize nearshore habitats along their migratory corridor but during their sub-adult and adult stages utilize deeper waters. Table 8 lists salmonid use of nearshore habitat in Washington's inland waters. Many of these species utilize estuarine and marine nearshore habitat along their migratory corridor to the open-ocean or deeper pelagic waters. Juveniles of these species are characteristic of shallow gravel-cobble, mudflats, and vegetated estuarine and marine nearshore habitats. The classifications used as Preferred Habitat Types describe habitat types in terms of wave energy defined by the WDNR classification system (Appendix A).

Pacific Salmon *(Oncorhynchus* spp.)

Pacific Salmon *(Oncorhynchus* spp.) depend upon a wide range of habitats throughout their life cycle (Groot and Margolis 1991). Upon emergence from the gravel redds of their natal streams, various salmon species and life-history stages exhibit wide variation in the extent of their use of various freshwater and saltwater habitats. Some species rear in their natal stream for a year or longer, others migrate immediately to the estuary, and some migrate to lakes. Some remain in freshwater habitats throughout their entire lifespan, while others engage in long outmigrations to the open sea. Others limit their outmigration to only the estuarine waters of Puget Sound. Some chum, pinks, and ocean-type chinook salmon outmigrate very soon following emergence from their natal stream gravels at sizes as small as 25 and 35+ mm fork length (FL).

The stresses young fry encounter upon entering estuarine waters is immense. Saltwater entry triggers a series of hormonal and physiologic changes. These changes transform them into smolts and adapt them to saltwater. Due to their dependence upon vegetated habitats, limitations to the extent of vegetated habitats pose a potential risk of reducing their ability to meet critical growth needs and counter predation risks.

Species that outmigrate at such small sizes have a strong reliance upon shallow-water habitats; especially those habitats vegetated with algae and eelgrass, for important prey resources and shelter from predation. Shallow nearshore habitats provide important shelter from size-selective predation by larger fish, most often found in deeper waters. In this way, shallow nearshore habitats are critical to the survival of such species (Healey 1982; Naiman and Seibert 1979; Simenstad 1979,1980, 1982; Johnson et al. 1997). For salmonids, mark and recapture studies in Hood Canal have identified this period of estuarine residence as one of critical growth and high mortality risk with estimated daily mortalities to be in the range of 31-46% (Bax 1983b; Whitmus 1979, 1985). This reliance on nearshore estuarine habitats may also make them particularly susceptible to productivity changes in those habitats when their growth determines their vulnerability to predation. Typically, upon growth to 50+mm FL when their vulnerability to size-selective predation is reduced, they begin to also utilize pelagic waters.

Studying migrating juvenile chum in Hood Canal, Simenstad (1979,1980) found chum to selectively prey on harpacticoid copepods found in very high densities in eelgrass beds. The study findings suggested links between the availability of harpacticoid crops, migration speed, and fish sizes. Smaller densities of harpacticoids appeared to link to faster migration speeds and smaller fish sizes. It was found that harpacticoid crops in eelgrass meadows at times averaged eight times the magnitude found in other nearshore habitats (Simenstad et al. 1979,1980). This is also consistent with Cordell's (1986) findings of the importance of the harpacticoid in juvenile chum diets. The affinity of the harpacticoid for eelgrass lies in the rich prey resources provided by epiphytic communities on and around the eelgrass shoots and rhizomes. The harpacticoid feeds on the diatoms, detrital, and microbial communities that make up the brown epiphytic felt accumulating on its shoots (Cordell 1999). Substrate type, depth, and wave energy are also important determining factors in prey abundance.

Chum (*Oncorhynchus keta*)

Timing of Salt Water Entry

Chum fry emerge from their natal gravels in early spring and outmigrate immediately to salt water throughout spring and early summer. Chum populations outmigrate as summer run, fall and winter runs. Of these runs, the summer-run chum fry outmigrate the earliest. Depending upon local temperature conditions, summer chum have been found to outmigrate as early as February and at sizes as small as 35 mm FL (Johnson 2001). With some variation between individual fish that are spawned at varying times throughout a run's spawning period, chum outmigration from their natal streams is an immediate outmigration to salt water (Simenstad

2001). In the case of summer chum; as the adults typically spawn relatively low in both large and small river systems, the fry outmigration to salt water is often a brief journey. This pattern of early outmigration places the summer chum in estuaries prior to many other salmonids (Johnson 2001). Their outmigration from freshwater is only a few days, and their subsequent stay in the estuary is estimated to be from one to a few weeks (Simenstad 2001).

Adult chum spawners also utilize nearshore areas as "staging" areas as they prepare for their migration to freshwater. This "staging" occurs in the proximity of the mouth of their natal stream. Quilcene Bay data suggests that summer chum mill about the mouth of the natal stream for 10-12 days before entering freshwater. This is thought to relate to maturation timing and acclimation to freshwater, but may also be affected by stream flows (WDFW/Point No Point Treaty Tribes 2000). Adult summer chum are known to return between August and October (Johnson 2001, Simenstad 2001). Later fall and winter runs are known to return through January (Simenstad 2001).

Estuarine Habitat and Prey Characteristics

Upon their arrival in tidal waters, chum fry inhabit shallow estuarine habitats, such as delta marshes, and flats, particularly those with dense eelgrass habitats, before starting to migrate along more narrow marine shorelines (Schreiner 1977, Bax 1982, Bax 1983a, Whitmus 1985; Groot and Margolis 1991; Levy and Northcote 1981). During this period, when they are fry <50 mm FL, juvenile chum restrict their movement to shallow waters ~0.5-1 m deep and often occur in dense schools during the day. At night, the schools are less cohesive and the fish appear to move offshore (Prinslow et al. 1979; Schreiner 1977). Their vertical distribution has been found to be concentrated in the top few meters of the water column (Bax 1983a). Chum fry tend to form loose aggregations during daylight hours and show a strong affinity for shorelines and low salinity waters (Schreiner 1977, Bax 1983a, Whitmus, 1985).

The fry appear to prefer quiescent shoreline waters. In studies of juvenile chum in Puget Sound marinas, Heiser and Finn (1970) found smaller chum fry (35-45 mm FL) to be reluctant to leave shorelines, while larger fry (50-70 mm FL) being observed to move offshore into deeper water upon encountering piers and bulkheads. During daylight hours, Kaczynski et al (1973) found chum fry in water less than one meter deep and within 3 m of Puget Sound beaches. During nighttime, Schreiner (1977) and Bax (1982) found Hood Canal chum to move away from the shoreline. Tyler (1963) found young chum in the Snohomish estuary to be within one meter from the surface and newly emergent fry a few centimeters from the surface. Healey (1980) determined that fry have an affinity to congregate near shorelines in depths of only a few centimeters during their early residence in estuarine waters. This is followed by a subsequent move to offshore waters as they reach sizes of 45-55mm (Healey 1982). Weitkamp (2000) reported juveniles to be primarily found in protected shoreline areas near the surface in waters less than one meter deep. Taylor and Willey (1997) observed chum 50-80 mm FL in size within 2 to 15 feet from dock structures and vertically located between the surface and depths of 3 m (10 feet). Consistently, juveniles appear to prefer shallow, low velocity waters. Schools of chum fry and other salmonids are found in marinas throughout the region (Taylor and Willey 1997; Heiser and Finn 1970; Weitkamp and Campbell 1980; Weitkamp 1981, 1982; Weitkamp and Shadt 1982; Penttila and Aguero 1978). In a study of juvenile salmon behavior associated with the Naval Fuel Pier at Manchester in Puget Sound, Dames and Moore (1994) found most chum migrating through the nearshore to be 60-80mm FL, while those migrating further offshore measured 90mm FL.

Tynan (1997) reports that as summer chum reach a threshold size of 50 mm FL, they begin a seaward migration at a rate of 7-14 kmd^{-1}. Rapid seaward movement possibly reflects a response to low food availability, predator avoidance, or a strong, prevailing south/southwest weather system accelerating surface flows (Bax et al. 1978, Simenstad et al. 1980, Bax 1982, Bax 1983). At a rate of 7 kmd^{-1}, southernmost outmigrating fry in Hood Canal would leave the Canal in 14 days (WDFW/Point No Point Treaty Tribes 2000). The food web of chum fry <50mm FL occupying shallow water habitats is principally upon detritus (i.e. dead plant material). Detritus provides the organic matter base for bacteria and other microbes that support epibenthic prey resources, such as the harpacticoid copepod. Certain taxa of harpacticoids appear to be commonly preferred by chum fry in estuarine environments (Kaczynski et al. 1973; Simenstad et al. 1980; Simenstad and Salo 1980; Simenstad et al. 1982). Naiman and Sibert (1979) estimated that more than 5 million fry require 3,850 kg of prey during their estuarine residence.

Pink (*Oncorhynchus gorbuscha*)

Timing of Salt Water Entry

Pink fry, among the earliest of outmigrators, arrive in estuarine habitats at very small sizes 25-30 mm FL in early spring. Similar to chum, they migrate immediately from spawning gravels very near to the estuary. Pinks have two-year life cycles with spawning occurring every other year. Depending upon the region, they will spawn in even or odd years. The predominant spawning pattern in Washington is the odd year pattern with most pink juveniles found in estuaries during even years. Although they basically use the same nearshore habitats as chum and small ocean-type chinook, it is likely that they may move offshore sooner spending less time in estuarine waters.

Estuarine Habitat and Prey Characteristics

During their early sea life, their estimated growth rate is 5% to 7.6% body weight per day (LaBrasseur and Parker 1964). It is estimated that this high growth rate requires an average daily food ration of 10-12% of their body weight (LaBrasseur 1969). Pinks are both opportunistic and generalized feeders that, upon occasion, may specialize in specific prey items. Along shallow cobble-sand and mud substrate beaches with low gradient shorelines, harpacticoid copepods are an important prey. In boulder and bedrock substrates with steeper gradient shorelines, calanoids and pelagic zooplankters are more important. Tidal currents are believed to play a significant role in the food delivery to these habitats. In addition to copepods, pinks have also been found to feed upon barnacle nauplii, mysids, amphipods, euphausiids, decapod larvae, insects, larvaceans, eggs of invertebrates and fishes, and fish larvae (Groot and Margolis 1991). Peak feeding appears to occur at dusk (LaBrasseur 1964).

Chinook (*Oncorhynchus tshawytscha*)

Timing of Salt Water Entry

Chinook show considerable variability in their outmigration timing. Chinook life-history structure divides into two races (ocean- and stream-type) (Healey 1991). In general, these are differentiated by ocean-type, showing an early outmigration to estuarine waters as subyearlings and the stream-type, who outmigrate from their natal stream only after their first year or longer. In addition to this general race distinction, there is considerable variation within each race that is believed to reflect uncertainties in juvenile survival and productivity within their respective freshwater and estuarine nursery habitats. They appear to spread the risk of mortality across years and habitats (Stearns 1976; Real 1980; Groot and Margolis 1991; Gilbert 1913, Reimers 1973; Schluchter and Lichatowich 1977; Fraser et. al.1982).

Ocean-type chinook enter saltwater at varying sizes along a continuum. Some enter salt water early as "Immediate" fry that migrate to the ocean soon after yolk resorption at 30-45 mm FL (Lister et al. 1971, Healey 1991). Others migrate out as fingerlings at varying sizes, 60-90 mm FL (Johnson 2001, Grette 2001), and others outmigrate as yearlings, who have remained in freshwater for their entire first year and outmigrate during their second or third spring (Myers et al. 1998). Both environmental and genetic factors underlie these differences in juvenile life history (Randall et al. 1987). It is believed that migration timing is linked to the distance of migration to the marine environment, stream stability, stream flow, temperature regimes, stream and estuary productivity, and general weather regimes. Due to their early outmigration to estuarine waters, ocean-type chinook more extensively utilize estuaries and coastal areas for juvenile rearing than those populations that reside longer in their natal streams. In general, the younger or smaller juveniles are at the time of emigrating to the estuary, the longer they are expected to reside in the estuary (Kjelson et al. 1982, Levy and Northcote 1982, Healey 1991). Although the majority of Puget Sound chinook generally outmigrates to the ocean as subyearlings, there is great variation across watersheds and tributaries. Twenty-seven recognized chinook stocks are found in the rivers of this region. These include 8 spring-run, 4 summer run, and 15 summer/fall and fall-run stocks (WDF 1993). Timing into the estuary can vary considerably depending upon the rearing environment. In the Sacramento-San Joaquin River estuary, fry were observed from January to March (Kjelson et al. (1981, 1982). In the Fraser River delta, fry were observed predominately in April and May (Levy and Northcote 1981, 1982). In the Puget Sound area, fry have been observed in estuarine habitat during the period from February to mid-September (K. Fresh, WDFW, unpubl.).

Estuarine Habitat and Prey Characteristics

In the estuarine environment, chinook tend to feed on a variety of prey resources along the estuarine gradient. These resources include aquatic insects and mysids in tidal freshwater and brackish zones and more benthic/epibenthic amphipods in euryhaline to euhaline habitats. Benthic amphipods, chironomid larvae, aquatic insects, mysids cladocerans, copepoda, and dipterans are their primary prey but certain taxa, such as (*Corophium* spp.) amphipods may be particularly selected in some habitats. Their diets also reflect seasonal changes in prey abundance. Evidence suggests growth rate variations between estuaries correlate with food supply with departure from the estuary being size-related. In the intertidal areas, chinook fry tend to prefer slightly larger prey organisms than similar sized salmonids. Their diets include larval and adult insects and various amphipods. Dunford (1975) suggests that chinook are more efficient predators of chironomid larvae than chum and able to eat prey that chum are unable to capture. In estuaries, chinook fry are generally shoreline oriented spending most of their time within 20 meters of shorelines (Weitkamp 2000). They have been observed utilizing nearshore areas including areas along shoreline structures, such as riprap, piers, and log rafts (Kask and Parker 1972; Ledgerwood et al. 1990; Meyer et al. 1980; Weitkamp et al. 1981; Weitkamp and Schadt 1982; Taylor and Willey 1997). In Fraser River tidal marshes, chinook have been observed using the high tide to reach the highest points along the shoreline. They were observed moving into tidal channels and creeks as the tide receded. With the incoming tide, they would again disperse along marsh edges (Healey 1980, 1982; Levy and Northcote 1981, 1982; Levings 1982).

Coho (*Oncorhynchus kisutch*)

Timing of Salt Water Entry

In North America, coho largely spend one winter in freshwater and migrate downstream as yearling smolts (Groot and Margolis 1991). Variations in outmigration range from the general pattern of populations that remain one, two or three years in their natal stream to those streams from which outmigration begins as fry. This latter group is an "ocean-type" coho that does not rear in their natal stream, but rather outmigrates as fry to brackish estuarine regions where it is presumed that they rear for extensive periods in tidal sloughs (Simenstad et al. 1992, 1993).

Estuarine Habitat and Prey Characteristics

Upon first entering salt water, coho feed upon marine invertebrates. As juveniles in nearshore habitats, they have been found to feed on copepods, mysids, epibenthic amphipods, and crab larvae (Miller et al. 1976; Simenstad et al. 1979). With growth, they soon become more piscivorous and become important predators on chum and pink fry (Parker 1971; Slaney et al. 1985). Their documented prey include fish such as Pacific sand lance, surf smelt, anchovy, and a variety of crab larvae. Smaller fish are found in shallow shoreline areas and larger fish are found in deeper channel areas of estuaries (Dorcey et al. 1978; Meyer et al. 1980; Durkin 1982; Argue et al. 1985; Dawley et al. 1986; Ledgerwood et al. 1990; Thom et al. 1989).

Sockeye (*Oncorhynchus nerka*)

Timing of Salt Water Entry

The majority of sockeye rear in lakes and tend to migrate as smolts during their second or third years of life. However sockeye have demonstrated several life-history pathways in adaptation to varying estuarine and nearshore conditions. Wissmar and Simenstad (1988) report that a common but not necessarily predominant strategy observed in the Fraser and Stikine Rivers is that of rapid migration to estuaries from fresh water and extensive estuarine rearing (Wood et al. 1987; Gilbert 1918, 1919; Schaefer 1951). Levy and Northcote (1981) also document sockeye fry rearing with pink, chum, and chinook fry in Fraser River marshes. It is believed that these varying life history strategies reflect responses to varying nearshore conditions and that these conditions are responsible for differences in marine survival between cohort populations (Groot and Cook 1987; Straty 1974; Straty and Jaenicke 1980). Although river/sea-type sockeye salmon have been rarely reported in rivers south of the Stikine River in Alaska (Gustafson et al. 1997), they have been reported in Southern British Columbia (Birtwell et al. 1987; Levings et al. 1995). The findings of Halupka et al. (1993) suggest that the lack of reported river/sea-type sockeye salmon stocks south of the Stikine River and Fraser River populations may be due to multiple factors. These include a lack of sufficient colonists with the genetic capacity for developing this life-history pattern and a lack of habitat suitable for development of this life-history pattern as well as their presence being overlooked. Riverine spawning have been reported, if only sometimes anecdotally, throughout the range of sockeye salmon (Gustafson et al. 1997). It is presently not known if this life-history strategy occurs in Washington State.

Steelhead (*Oncohynchus mykiss*)

In general, steelhead migrate through estuaries as smolts during the second and third year of life remaining in relatively deep water (Dawley et al. 1986; Ledgerwood et al. 1990). Although they are not found in large numbers along shoreline areas, they have been found in the Columbia River plume in May and early June. Individuals have also been caught in beach seines likely feeding on small fish migrating and rearing in nearshore habitats (Shreffler and Moursund 1999).

Coastal Cutthroat (*Oncorhynchus clarki clarki*)

The coastal or sea-run cutthroat life history is very complex and little understood. Although most anadromous cutthroat trout enter seawater as two or three year olds, some may remain in fresh water for up to five years before entering the sea (Giger, 1972; Sumner, 1972). Still other cutthroat trout may not outmigrate to the ocean, but remain in small headwater tributaries. Other cutthroat trout may migrate only within freshwater environments despite having access to the ocean (Tomasson, 1978; Nicholas 1978; Moring et al. 1986; Johnson et al. 1999). Similar to sockeye, cutthroat are large and tend to occupy relatively deep waters. However, individuals are observed and caught in nearshore areas. These individuals are believed to be likely foraging on small salmonids and forage fish present in nearshore habitats.

Bull Trout (*Salvelinus confluentu*)

In the northern Puget Sound region, bull trout populations show considerable variation in migration and rearing strategies (Kraemer 2001). There are populations that spend their entire lives in headwater streams, other populations that spend one or more years in the main stem larger rivers, and some that spend one or more years rearing in lakes.

The anadromous populations are characterized by fall spawning between September-November, depending upon the weather. As temperatures drop in fall to around 8 degrees C, they begin their move from the estuary to upriver over-wintering sites with spawning being triggered by falling water temperatures. Sexually mature fish can begin leaving the marine waters as early as late May with most fish back into freshwater by late July. They reach spawning staging areas one to four months prior to spawning. They tend to spawn in headwaters as far as 200km upstream from the river mouth. Sexual maturity occurs in the second fall with spawning occurring at age 4 or 5. Non-spawners return to over-winter in their natal stream, typically in the lower 40-50 km of the river and spawners return to spawn and over-winter in the headwaters. Consequently few fish are in the estuary between December and February (Kraemer 2001).

Timing of Salt Water Entry

Post spawning adults begin to re-enter marine waters around the first of January with older fish re-entering the estuary earlier and all spawners returned to the estuary by March. A smolt trap at the Skagit River indicated that the bulk of downstream migration of smolts and outmigrating adults occurred in spring with 95% outmigration between April 1st and July 15th and a peak in mid may to early June. There were variations in size. However, in general, they were 150mm in length (Kraemer 2001).

Estuarine Habitat and Prey Resources

During their nearshore residence, they are typically found along the shoreline in less than 3 meters of water. They are often seen actively foraging in less than 1/2 meter of water. Although, they clearly can and do cross deep water, as smolts, subadults, and adults, they appear to spend most of their time in the estuary in shallow water. They also tend to remain within tens of miles from their natal stream mouth. These shallow area shoreline oriented fish primarily forage upon baitfishes and they are capable of foraging on fish 35-45% of their own body size.

Sturgeon (*acipenser* spp.)

White sturgeon *(acipenser transmontanus*) live in large river systems such as the Fraser, Columbia, and Sacramento-San Juaquin Rivers. Populations in the Columbia River are isolated by dams but are reportedly healthy (Tracy 1993; Hanson et al. 1992). Some populations are land-locked and some migrate to marine waters. Spawning is between February and July. Spawn is broadcast in fast water and following dispersal adheres to bottom sediments. Hatching occurs in 7-14 days with larvae moving immediately into the water column (Brannon et al. 1985). After completion of the water column phase, larvae enter a phase of hiding in the substrate cover followed by an active feeding stage before metamorphosing into post-larval young-of-the-year sturgeon. Larval sturgeon are unable to tolerate salinities >11 ppt. Juveniles prefer deepwater habitats. It is believed that their survival is lower in shallow-water habitats due to predators (McCabe 1997). Benthos or periphyton dominates the diet of larval white sturgeon (Brannon et al. 1984) but they also feed on pelagic fry and zooplankton. Young-of-the-year feed on small crustaceans with *corophium* being a common food. Second and third year fish feed on tube dwelling amphipods such as mysids (*Neomysis* spp). Female sturgeons live about 34-70 years (Brennan and Cailliet 1989). The oldest male aged by Brennan and Cailliet (1989) was estimated to be 23 years old.

Estuarine Habitat and Prey Resources

Bajkov (1951) reported that sturgeon in the Columbia River tend to move downstream in late winter and early spring for return to the estuary or the ocean. Adults move out of the estuary in fall and migrate either upstream or into marine areas followed by spring and summer migrations into the estuary from upstream and marine areas (Bajkov 1949; Hanson et al. 1992). Juveniles rear in fresh or slightly brackish water for undefined periods (Bajkov 1951; Scott and Crossman 1973; Kohlhorst 1976; Kohlhorst et al. 1991). Hanson et al. (1992) reports that generally subadults use an estuary or river sloughs in the summer with movement upstream to use deep, freshwater areas in the fall and early winter.

Green Sturgeon (Acipenser medirostris)

Green Sturgeon *(Acipenser medirostris)* is much smaller than the white sturgeon. Their distribution includes the North Pacific coasts of Korea, China, northern Japan, the USSR to the Amur River (Berg 1948), and in North America from the Gulf of Alaska (Migdalski 1962) to San Francisco. They are considered rare in freshwater and appear to prefer the mouths or lower reaches of large rivers where they are see in August and September and are rarely found in fresh water (Carl et al. 1967; Scott and Crossman 1973).

Transient Fishes

Transient species (Table 9) move from subtidal to intertidal habitats to feed (Miller and Dunn 1980; Wolff et al. 1981; Rozas and Lasalle 1990; Van der Veer and Witte 1993), spawn, or avoid predation (Kneib 1987; Ruiz et al. 1993). These fishes share a dependence upon nearshore intertidal and subtidal habitats for one or more of their life-history stages but use deeper habitats in other stages. Table 9 also identifies the habitat type they depend upon and the life-history stage supported by a specific habitat type. Pacific sand lance, surf smelt, and rockfish species are examples of transient species that use nearshore eulittoral habitats on a temporally limited basis depending upon their life-history phase. Although, they use pelagic habitats as adults, they use eulittoral habitats for both spawning and rearing. Although Pacific sand lance and surf smelt share some similarities with juvenile salmon in their migratory utilization of nearshore habitats enroute to the sea or to adult neritic habitats, for the purposes of this paper, their obligate dependence upon nearshore habitat for spawning places them in the transient fishes classification. Rockfishes are classified as transient due to their combined dependence upon nearshore habitat for only part of their juvenile life stage and their move to adjacent deeper adult habitats. Their use of nearshore habitat is very transient in nature. Rockfish juveniles migrate and settle into nearshore habitat for a brief period of their existence to take advantage of the shelter and prey resources provided in those habitats (Haldorson and Richards 1987; Norris 1991; Love et al. 1991; Miller et al. 1976; Simenstad et al. 1979; Kuzis 1987; Matthews 1989). Upon reaching larger sizes, they move out to deeper adult habitats. Their adult home area is quite small (i.e. 50 m^2 or less). Their life-history strategy is not that of migrating through an area but rather, in the case of the nearshore, migrating into the area of the nearshore and moving back out to adjacent deeper waters utilizing floating, unattached nearshore vegetation as a transportation corridor to adult habitat.

Surf Smelt (*Hypomesus pretiousus*)

Surf smelt *(Hypomesus pretiousus)* spawn at high slack tide near the water's edge on coarse sand or pea gravel. Egg development is temperature dependent with marine riparian vegetation serving to maintain lower temperatures during high temperature periods (Penttila 2000a). The smelt life span is thought to be five years with the bulk of spawners being 2 years in age (Penttila 2000c). The adults feed primarily on planktonic organisms but their movements between spawning seasons are basically unknown. However, they are known to be a significant part of the Puget Sound food web for larger predators. Recent surveys document 205 miles of surf smelt habitat in Puget Sound (Penttila 2000b). In Washington, smelt spawning grounds are geographically distinct with significant differences in temporal use. Spawning in northern Puget Sound occurs year round, while spawning in central and southern Puget Sound occurs in fall and winter. For populations along the coast and straits, spawning occurs in summer months. Not all "suitable-looking" sand-gravel beaches are used by spawning surf smelt. The specific factors associated with surf smelt spawning sites, evolving over the relatively short time since establishment of the Puget Sound temperate marine ecosystem following the last Ice Age, are unknown. It is possible that suitable substrate, availability of adequate amounts of high intertidal beach surface, and availability of suitable adjacent larval nursery areas are the primary factors in determining spawning locations. The limited extent of surf smelt spawning grounds increases their vulnerability to shoreline development and construction activities with some spawning grounds being mere remnants of their historical extent (Penttila 2000a). Their spawning grounds have been mapped and are protected by the Washington Administrative code (WAC) Hydraulic Permit Approval (HPA) rules.

Pacific Sand Lance *(Ammodytes hexapterus)*

Pacific sand lance *(Ammodytes hexapterus)* spawn at high tide in the upper intertidal area on sandy gravel beach material. The fine sandy beach material coats the eggs and likely serves to assist in moisture retention when they are exposed during low tides. It also serves to conceal the eggs from predators. In Puget Sound, the spawning season is November 1 through February 15 with larvae commonly found between January and April in the Puget Sound area (Garrison and Miller 1982). Upon hatching, larvae and young-of-the-year rear in bays and nearshore waters. Although the metamorphosis of Pacific sand lance from larvae to juvenile stages has not yet been described, Smigielski et al. (1984) found that with the cogener (*A. americanus)* a complete metamorphosis occurs between 30-40 mm FL with burrowing behavior to escape predation occurring between 35-40mm and movement to deeper waters occurring at 50mm size length (Tribble 2000). At Friday Harbor, Washington, Tribble (2000) found sand lance larvae and juveniles to feed in the upper water column during the day upon prey items similar to juvenile salmon. These include such prey items as copepods, crab larvae, amphipods, and diatoms. Tribble (2000) also found swimming speed to appear to maximize at the 45mm size.

Adult movement and age structure are currently unknown. They feed in open water in daylight and burrow into the bottom substrate at night to avoid predation. They are a significant dietary component of many economically important resources in Washington, such as juvenile salmon. It has been found that 35% of juvenile salmon diets are known to be Pacific sand lance (Environment Canada 1994). They are particularly important to juvenile chinook with 60% of the juvenile chinook diet represented by Pacific sand lance. Their habit of spawning in upper intertidal zones of protected sand and gravel beaches makes them particularly vulnerable to the direct and cumulative effects of shoreline development. Their spawning habitat is also protected by the WAC HPA rules.

Rockfish (*Sebastes spp.*)

Rockfish *(Sebastes spp.)* inhabit rocky reef habitats as adults but use nearshore habitats to rear as juveniles. As adults, they do not venture outside of 50 m^2 from their preferred habitat. Born around April as free-swimming pelagic larvae, rockfish spend four months in open water (DeLacey et al. 1964). During their first year, juveniles settle into shallow habitats vegetated by bull kelp, macroalgae, and eelgrass to meet critical juvenile rearing needs (Haldorson and Richards, 1987; Matthews, 1990; Miller et al 1976, 1978; Norris 1991; Phillips 1984; Stober and Chew, 1984). These nearshore habitats provide juvenile rockfish shelter from predation and increased access to prey resources. Survival is likely dependent upon the availability of suitable refuge habitat provided by nearshore environments (Norris 1991). The particular nearshore habitats most utilized by juvenile rockfish are gravel habitats that provide benthic crustacean prey resources (Miller et al.1976). Copper, quillback, and brown rockfish species generally eat small fishes and epibenthic prey with their seasonal distribution likely reflecting prey presence. Summer feeding plays an important role in providing food for storing fat reserves for winter maintenance. They reproduce pelagically and as a viviparous species (also considered ovoviviparous by some classification systems), they give birth to live young. It is suggested that the availability of juvenile habitat may play a more important role than even the size of local adult fish density in predicting local recruitment success. These early nursery habitats likely play a determining role in fish stock density through prey resource access and protection from mortality during vulnerable juvenile stages. Limited availability of such habitat is thought to impose a demographic bottleneck on stock recruitment (Norris 1991; West et al. 1995). The seasonal variation in vegetated habitat is reflected in dramatic density differences (Buckley, R.M. 1997). Matthews (1989) found the highest fish densities in low-relief rocky reef and sand-eelgrass habitats to occur in the summer with fish density declines in those habitats consistent with dieback of vegetation. This is likely due to the lack of places for fishes to hide in these habitats when vegetation is lost (Matthews 1989; Quast 1968; Stephens et al. 1984; Ebeling and Laur 1988). Winter high fish densities in high-relief habitat likely correlate to the presence of holes and crevices in these habitats for fishes to hide in. Temperature has been found to affect juvenile rockfish growth during their first year with warmer temperatures, such as those found in the nearshore areas, found to produce higher growth rates and possibly increased food assimilation efficiency (Buckley, 1997; Love et al. 1991).

Juvenile rockfish also occur with drift habitat formed by macrophytes and seagrass for both prey resources and refugia while they move between pelagic and nearshore habitats (Bohlert 1977; Buckley 1997; Shaffer 1995).

Dislodged nearshore vegetation may provide a link between pelagic and nearshore systems by providing a transportation corridor in the form of refuge and prey resources for small fishes settling into or exiting the nearshore environment. Under the influences of tide, wind, and ocean-current-driven convergent zones, detached intertidal and subtidal vegetation form floating mats that move into open water pelagic systems. These floating mats provide cover for small rockfishes along with high densities of planktonic organisms associated with the vegetation (Gorelova and Fedoryako1986). This nearshore and pelagic mix creates a unique habitat offering components of both the nearshore vegetated habitats and open water pelagic system. Depending on the season, such vegetation mats have been shown to provide higher abundances of species diversity and richness than is usually found in open water systems. In this way, it acts as a nutrient, larvae, juvenile fish, and pollutant distribution system between nearshore and benthic habitats (Johnson and Richardson 1977; Kulczycki et al. 1981; Kingsford and Choat 1986; Shanks and Wright 1987; Kingsford 1992; Shaffer 1995). Such drift habitat may be a critical resource for many fish species in Washington coastal waters for such species as juvenile chum, pink, chinook, and coho salmon, surf smelt, Pacific herring, and northern anchovy (Simenstad et al. 1991a).

Macroinvertebrates

Macroinvertebrates include benthic and epibenthic shellfish that are an economically important resource in Washington State and are harvested for recreational purposes as well as by commercial industries**.** Shellfish habitats vary across estuarine and marine nearshore habitat. Shellfish rely on a variety of intertidal habitats specific to the life-history strategies of each species. Of particular concern is their proclivity, as filter feeders, to incorporate contaminants in their tissues and pass those contaminants to their predators in the marine food web. Filter feeding makes shellfish particularly susceptible to ingesting contaminants from the water in which they live. These accumulated water and sediment contaminants can then be passed through the food chain to shellfish predators.

Bivalves

Bivalves (clams, mussels and oysters) feed by filtering large quantities of water through ciliated gills drawing water into the mantle cavity and passing it back out. By drawing water over the gills, microscopic food becomes trapped in mucus and moved along cilia-covered pathways to the mouth (Kozloff 1983).

In the lower reaches of the intertidal zone, substrate preferred by bivalves is composed largely of gravel mixed with sand or mud, which is an ideal habitat to support littleneck clams (*Protothaca* spp.). The bent-nose and other clams of the genus *Macoma* reach peak abundances in muddy sand. Similarly, the large gaper and horse clams of the genus *Tresus* generally live in sandy mud, or a mix of mud, gravel, and shell. The heart cockle (*Clinocardium)* appears to prefer quiet bays with fine muddy sand substrates. Soft-shell clams (*Mya arenaria)* are found typically in sand and mud or in mud and gravel habitats in areas where there is reduced salinity due to fresh water seepage. Other bivalves, such as oysters and mussels require a hard substrate to which they attach.

Geoducks Clams (Panopea Abrupta)

Geoduck clams *(Panopea Abrupta)* dominate the biomass of benthic infaunal communities in many areas throughout Puget Sound (Bradbury et al. 1999). This large burrowing clam can be found from Alaska to California in lower intertidal areas and out to depths exceeding 120 meters. Although, they are found in a variety of substrates, geoducks tend to recruit to substrates of sand/mud. Geoducks are the largest burrowing clam in the world and weigh an average of 1.9 pounds in Puget Sound. However, they can reach weights of ten pounds. Geoducks are broadcast spawners that spawn from April and into July, with major gamete releases occurring in June. Following release of gametes by spawning adults, larval clams drift with the currents for three to five weeks and settle to the substrates. Geoducks feed on planktonic algae drawn through their long necks (Boyle and Wilkerson 1985). Geoducks begin to reproduce at approximately 4 or 5 years of age and are able to reproduce annually for the remainder of their lives. The average life span of a geoduck in this region's is 46 years (Bradbury and Tagart 2000) with the oldest geoduck recently found to be 163 years old. Given their long life span, geoducks are presumed to have a low rate of recruitment and increase. It is possible that geoduck larvae in the Port Gamble area settle from as far away as Canada as well as nearby adjacent areas. Juveniles appear to cluster around adults. The causal mechanism behind this cluster relationship is unknown but the clustering is documented. Juveniles are consumed by a variety of marine animals but adults are primarily consumed by the seastars (*Pycnopodia helianthoides* and *Pisaster brevispinus)* (Bradbury 2001). The major limiting factor for geoduck production is the very low rate of recruitment. Although the clams grow rapidly, it can take 30 to 60 years for a harvested population to be naturally replaced (Boyle and Wilkerson 1985).

The geoduck clam fishery is the most economically important clam fishery on the Pacific Coast of North America (Campbell et al. 1998, Hoffmann et al. 1999). In Washington State, geoduck resources are inventoried and assessed by the Washington Department of Fish and Wildlife and owned by the Washington State Department of Natural Resources (WDNR). WDNR conducts public auctions of geoduck harvest quotas. Under the Rafeedie decision, the Tribes are entitled to up to 50% of the Total Allowable Catch (TAC) of the commercially available wild stock of geoducks. The State harvests the other 50%. It is this 50% of the TAC that DNR auctions. The harvest of geoducks generates between $6-8 million per year for the citizens of the State of Washington. DNR, WDFW, as well as many cities, counties, tribal governments, and others receive money ultimately generated by the harvest of geoduck either through the ALEA grant program or by specific direction of the Legislation. Geoducks are important members of Puget Sound benthic communities. Shaul and Goodwin (1982) report that a conservative estimate as to the total commercially available biomass in the shallow subtidal areas (-18 to -70 feet MLLW) in Puget Sound is 163 million pounds. Annually the commercial fishery is allowed to fish at a harvest rate of 2.7% of the commercially available biomass. Geoducks have been managed for harvest for 30 years. Their populations are presently stable.

In a study of geoduck growth in the Port Gamble area, Shaul and Goodwin (1982) compared geoduck growth and population parameters in a dredged navigation channel against those found in a nearby-undredged area. The dredge activity had occurred in 1957, 26 years prior to the sampling. Shaul and Goodwin (1982) found that only a small fraction of the population likely survived the dredge activity. Out of 275 geoducks sampled from the navigation channel, only 31 were older than 26 years. The average age of these geoducks was 18 years; well below the region's average of 46 yrs of age and well below the 28 year mean average of those clams found in the undredged area. Geoduck age can be determined by counting growth bands appearing on their shells that are similar to the rings of trees. The shells of the surviving 31 geoducks in the dredged area displayed that a stressful event occurred 26 years earlier through consistent anomalies or checks in the shell growth lines through the survivor population. Presently, the effects of dredging on geoduck recruitment and recolonization following dredging are unknown.

Crabs and Shrimp

Dungeness Crab (Cancer magister)

Dungeness crab *(Cancer magister)* rely on eelgrass beds, shell deposits, oyster culture, and macroalgae habitats of the intertidal zone during their developmental stage of 'settlement'. The life cycle of this species is complex, with shifts in habitat location depending on age of the individual, although rate of growth is highly variable (Botsford 1984). In Washington, along the coastal waters, the Dungeness crab breed from May to June, with the fertilized eggs extruded in September to October. Around January through March, the meroplanktonic larvae are released by broadcast manner to the waters. The larvae develop through five zoel stages to a megalopae stage, taking approximately 120 to 150 days. After the megalopae stage, the young crab settle to the benthos around May to June (McConnauaghey et al 1995). Nearshore habitat in shallow embayments and inland waters provide crab nursery sites that are rich in prey resources, predation shelter, and warmer water temperatures to meet important growth needs. Crabs settling or residing in estuaries and shallow embayments are found to have significantly higher growth rates than their cohorts of the same year-class settling in coastal environments. The Dungeness crab is considered a benthic predator and feeds for rapid growth during its residence in estuaries and offshore communities (Stevens and Armstrong 1984). Stevens (1981) reports the diet of small crabs (average size - 39.7 mm carapace width) to be dominated by small bivalves and crustaceans, while adult crab consume bivalves, fish, isopods, amphipods and crangon shrimp (Gotshall 1977; Bernard 1979).

The highest abundance of juvenile Dungeness crab is found in the intertidal zone during late summer (July through September) with a lower, more constant density in winter and early spring at this zone. Juvenile growth is correlated to water temperatures with the higher temperatures of late summer giving rise to peaks in growth rates, whereas during the colder periods, between November and March, less growth was found to occur. Growth increases begin again after March and peak in August (McMillan et al. 1995). In a study of northern Puget Sound intertidal habitat, McMillan et al. (1995) found the highest crab densities were consistently found in the gravel-algae and eelgrass habitats while significantly lower densities were found in open sand habitat.

Survival rates for the Dungeness crab were found to differ between habitats, with high survival in gravel-algae and lower survival in eelgrass and open sand habitats. Increased survival rates are attributed to the gravel-algae habitat areas where the substrate is more reticulated and there is an overstory of attached or drifting macroalgae. In contrast, crab survival rates are lower in areas with small stands of eelgrass and open sand habitat. Crab density increases have been found to correlate with increases in percent eelgrass cover. Studies by Nelson (1981) and Heck and Thoman (1984) determined that a minimum, or threshold, vegetation density is required for significant reduction of predation impacts. Such distribution shifts have been found to be consistent to predation-influenced patterns known for other crustacean fauna in vegetated aquatic habitats (Nelson 1981; Heck and Orth 1980; Heck and Thoman 1984; Summerson and Peterson 1984; Orth and van Montfrans 1987; Wilson et al. 1987; Heck and Wetstone 1977; Nelson 1981; Orth et al. 1984; Leber 1985; Heck and Wilson 1987).

Juvenile Dungeness crabs settle in northern Puget Sound from June through September, while coastal settlement occurred only during May and June (Stevens and Armstrong 1984; Gunderson et al. 1990; Dumbauld et al. 1993). Upon reaching approximately 30 mm in size, *C. magister* migrate from eelgrass habitat to deeper unvegetated subtidal areas. Gunderson et al. (1990) found that during the spring, following settlement, the majority of those juveniles initially settling off the coast migrated into estuaries to join those (now larger) members of the same year class that had moved into estuaries at an earlier age. This movement substantially increases the abundance of one-year old crabs in estuaries compared to adjacent coastlines. Predation is a major contributor to mortality during this time therefore; refuge availability provided by eelgrass, shell material and macroalgae is particularly important. At the Gray's Harbor area, mature female crabs tend to leave the harbor to offshore areas for spawning (Stevens and Armstrong 1984). Armstrong et al. (1987) found virtually all of the ovigerous female population at Ship Harbor to be located in the eelgrass zone from about 0.5 to 4.0 m depth buried in the substrate. The availability of intertidal habitat and refuge are important contributing factors to maintaining a viable crab population (McMillan et al. 1995).

Even though predators of *C. magister* are found in higher concentrations in estuaries than off the coast, the Dungeness crab will spend up to two years in the estuarine environment (Gunderson et al. 1990). It is believed that crabs utilize estuaries, despite the risk of increased predation, because of the advantage of increased food availability, which greatly enhances their growth rates (Gunderson et al. 1990). Predators of *C. magister* include coho and chinook salmon who prey heavily on *C. magister* megalopae (Reilly 1983). In Humboldt Bay, Prince and Gotshall (1976) found *C. magister* megalopae and postlarval instars to be the most important food items for copper rockfish (*Sebastus caurinus)* (Fernandez et al. 1993). Armstrong (1991) reports that over 50% of a settling crab year-class could potentially be lost by sculpin predation. Jacoby (1983) and Gotshall (1977) report cannibalism among young-of-the year and by larger crabs on smaller crabs as a factor of predation rate.

Dungeness crab recruit to the fishery at 3.5 to 5 years after settlement. The earlier 3.5 recruitment year is possible when young crab have ideal habitat conditions with adequate food, proper salinity levels and the right temperature regime during their early growth period (Armstrong, et al 1987).

*Shrimp (***Crangon spp***)*

5.4.2.2. Shrimp (*Crangon* spp) live in shallow water areas and burrow under the sand. *Crangon* spp. is an important prey source to many estuarine organisms including Dungeness crab (Armstrong et al 1981). The ghost shrimp (*Neotrypaea californiensis*) burrows in the substrate as well, but it prefers the more muddy sand areas with high amounts of clay or organic matter (Kozloff 1983).

Dredging in Washington State

Marine dredging can be generally characterized as either: 1) dredging for the creation of new projects and waterway deepening or 2) maintenance dredging to maintain existing facilities hydrologic features. New construction dredging is defined as any modification that expands the character, scope, or size of an existing, authorized project. In contrast, maintenance dredging is limited to the same character, scope, or size of an existing authorized project. Maintenance dredging tends to occur periodically at existing navigation channels due to the continuous deposition of sediments from freshwater runoff or littoral drift and poses different risks and alterations to marine ecosystems than the nature of those risks posed by new construction. By far, most dredging in Washington State has been maintenance dredging. Those waterways requiring deepening have been limited to the larger ports such as Seattle and Tacoma; which have required channel deepening for deeper draft vessels (Vining 2001).

Marine dredging in Washington State is usually conducted for one of the following six reasons:

- Maintaining water depths suitable for the navigation of vessels
- For new construction, such as creation or expansion of marinas, or to enlarge and deepen channels and port facilities to accommodate larger vessels
- Mining of gravels and/or sand at the estuary or mouth of large rivers for commercial purposes (see also white paper on *Fresh Water Dredging* for more information on gravel mining)
- Conveyance of flood flows (e.g. Cedar river)
- Dredging for beach nourishment at other sites
- Removal of contaminated sediments, or construction of nearshore or subtidal confined disposal facilities for confinement of contaminated sediments
- Cement Production - to provide cement production materials

Marine dredging excavation may also be utilized on a short-term basis for utility or transportation projects, where an area is trenched out for the installation of underwater pipelines, cables or for laying bridge supports. Dredging may also be performed to remove and replace unsuitable materials with suitable fill for grading purposes.

For the purposes of this paper, marine dredging activities also include the disposal of dredged materials in marine areas. Dredged material disposal includes the activities associated with the dredging operation where the materials are deposited at a different marine site from where the sediments were removed.

General Dredging Locations

Similar to the PSDDA program, in this paper, the locations of marine dredging activities in Washington State are characterized by region. The four major areas are described as follows and are illustrated in Figure 3:

- Puget Sound (i.e. inlets and bays of the Strait of Juan de Fuca and the Georgia Strait, Bellingham, Anacortes, Swinomish Channel, Everett, Seattle, Lake Washington, Tacoma to Olympia)

- Grays Harbor, Willapa Bay, and Quillayute coastal estuaries

- Columbia River from the mouth up to river kilometer 60 (river mile 38). Given the present state of knowledge concerning salinity intrusion, kilometer 60 (river mile 38) is a conservative maximum. Dredging above kilometer 60 is considered "freshwater dredging". (See associated white paper on *Fresh Water Dredging*). Note: Federal regulation of much of the dredging activities along the Columbia River is managed by the U.S. Army Corps of Engineers' Portland District.

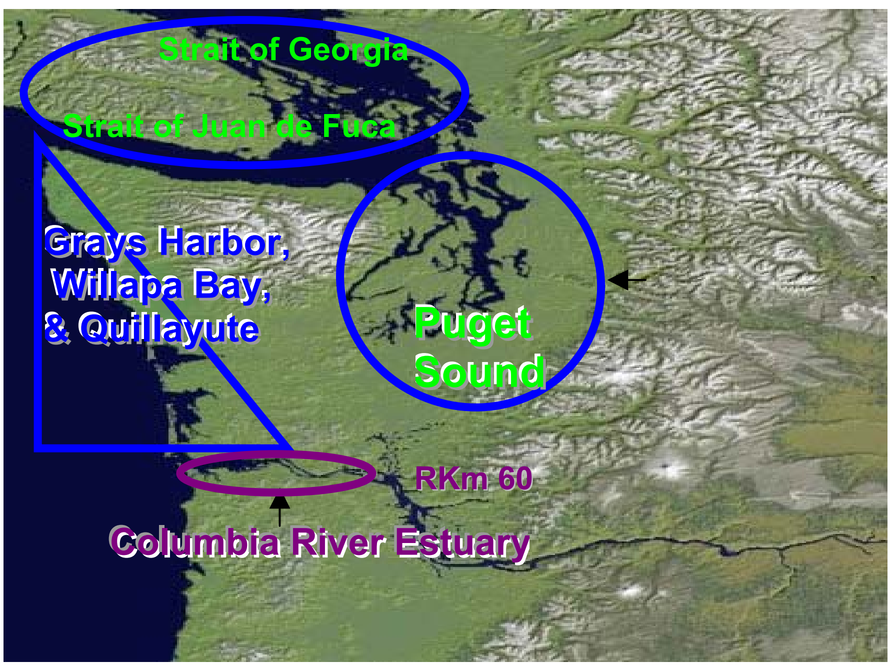

Figure 3. Marine Dredging Activities by Region in Washington State

Dredging Methods and Equipment

There are many varieties of dredges, including specialty dredges that are used for particular situations in Washington's estuarine and marine waters. Dredge method selection is driven by the nature of the sediments and the types of disposal required for those sediments respective to a given site. Equipment selection depends upon the following factors:

- Characteristics of the material to be dredged
- Quantities of material to be dredged
- Dredging depth
- Distance to disposal area
- Physical environmental factors of the dredging and disposal area
- Contamination level of sediments
- Methods of disposal
- Production required
- Dredge availability

Dredging methods are divided into two primary categories, **Hydraulic and Mechanical.** Under each category there are a variety of equipment types. Figure 4 indicates the variations in these two general categories of dredge types.

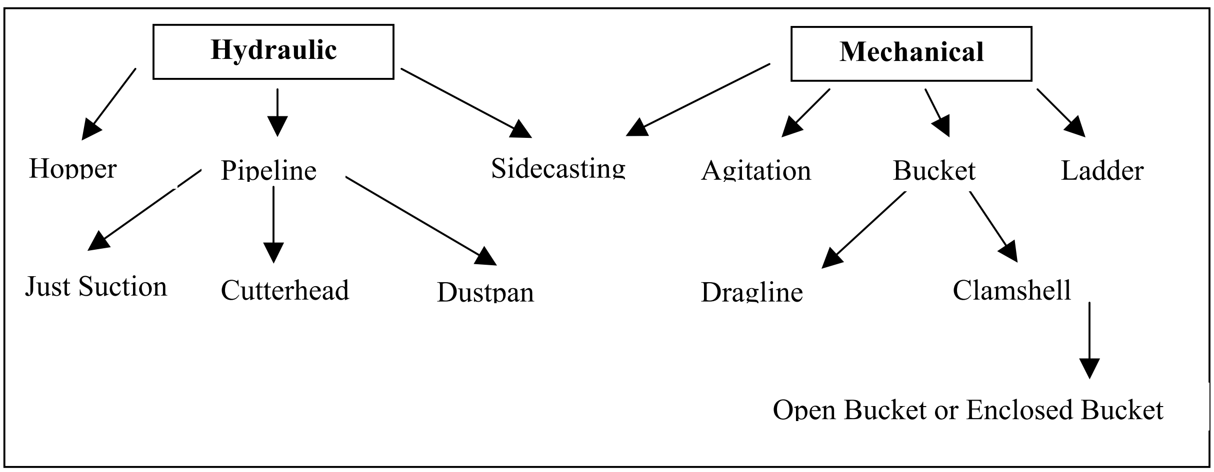

Figure 4. Dredging Methods and Equipment

Common Dredging Methods

Mechanical dredges are reportedly the most commonly used dredging method in Puget Sound (USACE 1983). Generally, mechanical dredging is used at the larger ports and embayments of the Puget Sound and the Straits area with small-scale suction dredging being used for marina projects and under-pier clearing. In Grays Harbor and Willapa Bay, suction and hopper dredging are utilized except in the upper reaches of the navigation channel such as along the Chehalis River, where clamshell dredges are used. The type of equipment used for marine dredging at the lower reaches of the Columbia River includes the clamshell, hopper, and pipeline dredges. Specialty dredges may be required for special substrate and site conditions. Francingues (2000) provides further complete description of specialty dredges.

Hydraulic - Hopper and Cutterhead Dredges

Hydraulic dredging is reserved for a limited number of under-pier or other "special needs" projects, and typically involves relatively small volumes of dredged material. Hydraulic dredging involves the use of water mixed with sediments that forms slurry. With suction dredges, a system of pipes and centrifugal pumps are used to produce a vacuum on the intake side so that atmospheric pressure forces water and sediments into the suction pipe. The section of pipeline that breaks up sediments at the bottom surface can be a cutterhead or water jets. The slurry of sediments and water is pumped either through a pipeline onto a barge or into a hopper bin for off-site disposal. The material may also be placed directly from the pipeline and side-cast away from the channel being dredged. Projects using hydraulic methods with direct placement from the pipeline include Snohomish River, Keystone Ferry Terminal, and Quillayute River.

Hopper Dredges

Hopper dredges are ships with both a suction pipe for dredging and a large hull for holding and transporting the dredged material. Dredged material is raised by dredge pumps through suction pipes connected to dragheads in contact with the bottom substrate. The draghead is moved along the bottom surface as the vessel slowly moves forward. Some dragheads also have cutterheads attached, which consist of moving cutting blades that help loosen and excavate the sediments. Dredged material is sucked up the pipe with the force of centrifugal pumps, and the sediment and water mixture (i.e., slurry) is transferred from the pipeline to the hopper bin. Because the hopper dredge is self-contained, once the vessel is filled to capacity, the ship carries the dredged materials directly to in-water disposal or beneficial use sites. Dredged materials are then released by opening up the hull. Most hopper dredges are also equipped with pipeline and pumps that may be used to transfer the materials directly to an upland or beneficial use site, or where the materials can be transported further by train or truck to a disposal or beneficial use site. Hopper dredges are limited to deep waters and they cannot dredge continuously. Excavation is less precise than with other dredges and hopper dredges have difficulty dredging steep banks and consolidated materials. Hopper dredges are effectively used in exposed areas.

To reduce the potentially high costs associated with traveling to and from a disposal area, maximum solids loading is attained in the hopper. When dredging coarse sediments with high-settling velocities such as sand, gravel, and rock, a maximum load can be obtained by overflowing clear water from the hopper (Scott 1992). Overflows during the dredging of fine silt sediment loads pose the risk of increased turbidity levels as the suspended sediments are released into the water column and are. All overflows are regulated for consistency with water quality requirements.

Cutterhead Pipeline Dredges

Cutterhead pipeline dredges use a rotating cutter device that is attached to a suction pipe. Sediments loosened by the cutterhead are transported through the pipe in slurry and deposited either on land or on a barge for aquatic disposal. The cutterhead has the ability to excavate most materials and pump directly to a disposal site. It is able to dredge almost continuously and reduce the use of blasting to dredge some rock bottoms. Cutterhead disadvantages include a limited capability in rough weather and typically not being self-propelled. The required pipeline can also be a temporary inconvenience to navigation.

Mechanical - Clamshell, Modified Clamshell, and Dragline Dredges

Mechanical clamshell dredging involves the removal of all kinds of materials for new construction or maintenance projects, whereas hydraulic dredging is used to remove loosely compacted materials and is more often for maintenance work. The equipment is similar to earth-moving machinery seen on land for development of new construction sites and includes clamshell and dragline dredges. Mechanical dredges remove bottom sediment by mechanical force, dislodging and excavating the material.

Clamshell or Bucket Dredges

Clamshell or bucket dredges have a bucket of hinged steel with a "clamshell" shape that is suspended from a crane. The crane is mounted on a barge, and during the dredging operation an anchoring system with tugs and/or spuds is used to control and position the barge. The bucket, with its jaws open, is lowered to the bottom surface. When the force of the bucket weight hits the bottom, the clamp grabs a section of sediments. As it is hoisted up, the jaws close, carrying sediments to the surface. Sediments are then placed on a separate barge or scow for transport to a disposal site. Clamshell dredges are well suited for work in shallow waters and in confined areas near shoreline structures such as piers.

Closed Environmental Bucket Dredges

Closed environmental bucket dredges are modified clamshell dredges with features that help minimize re-suspension of sediments. Closed buckets have a number of designs with several being designed specifically for the dredging of contaminated sediments. Basically, the closed bucket design is intended to reduce sediment spill or flow out during digging, lifting, and exiting the water surface in order to minimize short-term impacts. The modifications of this equipment such as overlapping side plates and rubber seals help keep sediments from spilling back into the water column during lift-out. However, these same modifications that ensure a tight seal also reduce the digging capacity and restrict its applicability to dredging loose, unconsolidated material (Wang et al. 2000). When the bucket is lowered to the surface in the open jaw position, it is designed to take a level cut out of the substrate by hitting the bottom surface with a parallel bite rather than with the more sharply angled bite of the traditional clamshell. This helps to keep sediment from dispersing during the dredging operations. However, in an evaluation of closed bucket effects, Hayes et al. (1984) found that a closed bucket reduced suspended sediments in the middle and upper water column by 35-45 percent, but increased suspended sediments in the lower water column. An evaluation of closed buckets for the Port of Seattle's East Waterway Deepening (Wang et al. 2000) indicated that site-specific substrate characteristics likely determine the net positive water quality benefit of the closed bucket compared to the open bucket technology.

Dragline maintenance dredging for vessel navigation is used at the mouth of the Quillayute River to provide access to La Push harbor, the only harbor of refuge for vessels along the Washington

Coast between the Strait of Juan de Fuca and Grays Harbor. Dragline dredging and side casting allows for the removal of sediments from the entrance channel and the re-use of those sediments to enhance a nearby surf smelt beach.

Mechanical-agitation and Directional Drilling

Agitation Dredging

Agitation dredging is accomplished by moving fine-grained sediments into the current of an ebbing tide, thereby allowing the movement of the tide and fluvial current to carry the sediments downstream and potentially out of the estuary. Bottom material is raised into the water column by using equipment such as a prop-wash, vertical mixer, drag beam, water, or aeration jets. Although it was a method previously used in areas with strong tidal or river current influences, prop-wash dredging is rarely utilized in Washington State at this time.

Directional Drilling

Directional drilling is an alternative to open trench dredging and is used on a short-term basis for the installation of underwater pipelines, cables or for laying bridge supports.

Transport and Disposal of Dredged Materials

After the sediments are collected from the removal site, they are either transported by the dredge (e.g., hopper) itself, or by the use of additional equipment such as bottom dump barges, flat deck scows, or pipelines with pumps. Dredged material disposal sites are divided into three categories: (1) open-water unconfined disposal sites; (2) open-water confined disposal sites, or (3) upland confined disposal sites.

Volumes of Material Dredged

Responsible for maintaining navigable waterways, the Army Corps of Engineers also regulates dredging activities under the Clean Water Act. In Washington State, the management of dredging and disposal pursuant to the Clean Water Act is accomplished through an interagency approach that includes ACOE, Seattle District; EPA, Region 10; Washington Department of Ecology (DOE), and the Washington Department of Natural Resources. This cooperative management is the Dredged Material Management Program (DMMP). Three separate programs are combined under the DMMP: the Puget Sound Dredged Disposal Analysis (PSDDA), Grays Harbor and Willapa Bay, and the Lower Columbia River programs. The Columbia River jurisdiction is shared with ACOE, Portland District.

Volumes of materials dredged are reported to the Dredged Material Management Program (DMMP) agencies. These agencies, which all regulate some aspect of dredging or disposal, are: the US Army Corps of Engineers, the Washington Department of Natural Resources, the Washington Department of Ecology, and the US Environmental Protection Agency. Annually, including the amount of dredged sediment removed from the Columbia River estuary, an average of approximately 7 million cubic yards (cy) (e.g. 5.3 million cubic meters) of sediments are dredged from Washington State waterways. This dredging has been primarily for the purpose of maintaining navigation systems for commercial, national defense, recreational purposes, and maintaining existing geomorphologic and hydrologic characteristics. According to the DMMP report, annual dredging volumes for 1998 and 1999 were approximately 4 to 6 million cubic yards from the Columbia River estuary, approximately 1 to 3 million cubic yards from Grays Harbor, Willapa Bay, and Quillayute combined, and approximately 600-800 thousand cubic yards from Puget Sound and the Straits (Cole-Warner et al. 2000).

Over many decades, dredging, diking, and various land-use activities have altered the shapes and hydrology of freshwater streams and rivers and the estuaries they drain into. These hydrologic alterations can effect dramatic changes in sediment transport mechanisms reducing the stream's ability to drop sediments at upland meanders and increasing the downstream flow of water and sediments, in some cases, into an estuary. These alterations combined with dredging in the estuary itself have, over time, altered key habitat controlling factors, such as bathymetry, substrate, salinity regime, current patterns, and wave energy that determine the nature of these habitats and the rich variety of marine organisms using those habitats. Although it is recognized that estuaries are dynamic systems impacted by the combined action of many mechanisms, this paper has treated dredging effects somewhat in isolation from the other mechanisms of impact. This paper takes the position that addressing potential long-term effects requires the recognition of multiple stressors, anthropogenic and natural, across the landscape and the need to conceptualize and prioritize restorative and compensatory actions on a long-term basis.

1998/1999 Dredging Projects

Dredging Permits issued in the 1998/1999 report period included permits for the Port of Anacortes, Oak Harbor Marina, Keystone Ferry Terminal, Port Gardner Outfall Replacement, Port Townsend Marina, Kingston Passenger-Only Ferry Project, Port of Seattle Pier 66, East Waterway Project (USACE/POS), Duwamish O&M, Hurlen Const/Boyer Alaska Barge Lines, Duwamish Yacht Club, US Navy Puget Sound Naval Shipyard, Hylebos Wood Debris Group Project, US Oil, Blair Waterway Deepening (USACE/Port of Tacoma), Port of Tacoma-Sitcum Waterway, Port of Tacoma - St. Paul Waterway, Olympia Harbor, and Newport Shores - Canal Entrance.

Dredge Material Disposal

Disposal Techniques

Chemical tests for the presence of chemicals that indicate the potential for unacceptable adverse environmental or human health effects determine the suitable disposal method (i.e. unconfined, open water disposal or confined disposal. Sediments assessed to be unacceptable for open water placement are typically placed in confined disposal facilities (CDF's). Disposal alternatives are determined through initial evaluations of the sediments to be dredged. Dredge materials identified through chemical tests to be contaminated are further evaluated biologically for effluent, runoff, leachate and plant and animal uptake characteristics. From these evaluations, disposal techniques are selected. Disposal techniques include open-water disposal, confined disposal, or beneficial uses.

Open-water Disposal

In open-water disposal, the potential for environmental impacts is affected by the physical behavior of the open-water discharge. Physical behavior is dependent on the type of dredging and disposal operation used, the nature of the material (physical characteristics), and the hydrodynamics of the disposal site. Dredged material can be placed in open-water sites using direct pipeline discharge, direct mechanical placement, or release from hopper dredges or scows. Use of direct pipeline discharge to open water is rare in Washington. Figure 5 is a conceptual illustration of open-water disposal techniques. Open-water disposal maybe confined or unconfined depending on the physical and chemical nature of the sediments and the goals of a project.

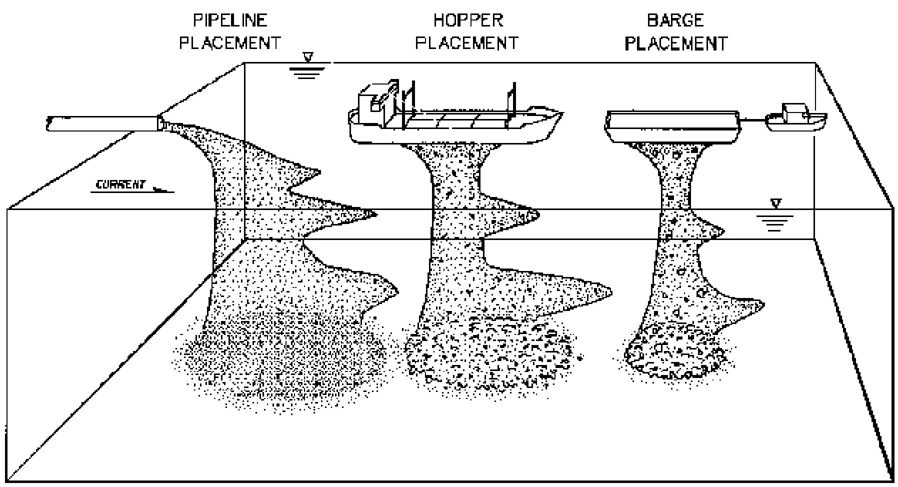

Figure 5. Open-water Disposal Techniques
(USEPA 1992)

Open-water disposal sites can be either predominantly nondispersive or dispersive. At nondispersive sites, the material is intended to remain on the bottom. At dispersive sites, material may be dispersed either during placement or eroded from the bottom over time and transported away from the disposal site by currents and/or wave action.

Confined Disposal Facilities (CDF's)

When chemical testing results indicate an existing potential for unacceptable adverse environmental and human health effects, the possibility of unconfined, open water disposal is eliminated. Confined disposal areas, confined disposal sites, diked disposal sites, and containment areas refer to structure engineered for containment of dredged material. The confinement dikes or structures in a CDF encloses the disposal area above any adjacent water surface and isolates the dredged material form adjacent waters. For this paper, confined disposal does not refer to subaqueous capping or contained aquatic disposal (CAD). Figure 6 is a conceptual diagram of a CDF.

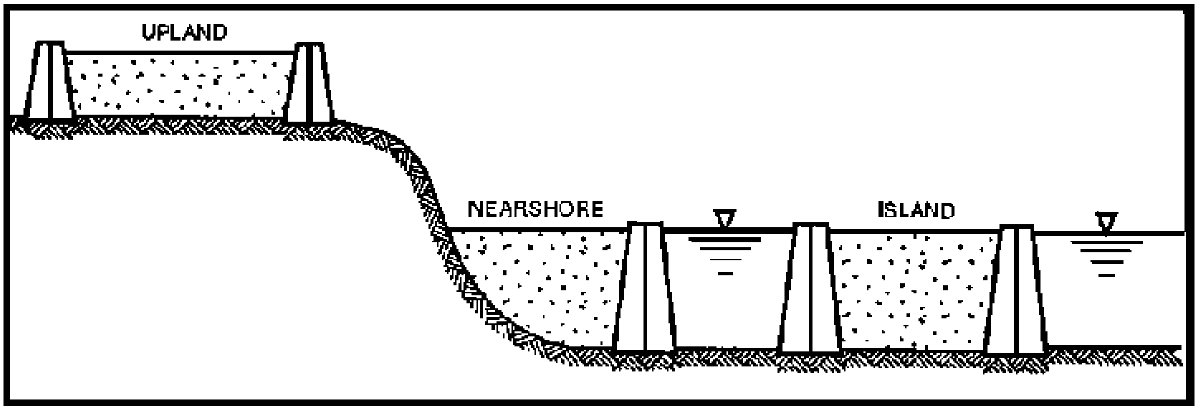

Figure 6. Confined Disposal Facility
(USACE 1992)

Capping

Capping is a protective measure to protect benthic communities from contamination, and thus also to prevent benthic-pelagic ontogenetic or trophic couplings from transferring contaminants to other communities. It more often simply involves the controlled placement of clean cap material on top of *in situ* contaminated material at an open-water site covered by a cap of clean isolating material. Much less frequently does capping involve prior movement/disposal of contaminated material. Various factors such as material characteristics, water depth, and hydrodynamics influence the fraction of material lost to the water column. However, it is common for such losses to be less than 5% (Gries 2001). Capping feasibility is determined by the evaluation of site bathymetry, water depth, currents, wave and climate conditions, physical characteristics of contaminated and capping sediment, and available placement equipment and techniques. In the interests of longevity, capping is considered to be more technically feasible in low-energy environments. (Truitt et al. 1987a, 1987b; Palermo 1991a, 1991b, 2000; Palermo et al 1992, 1998). Recent juvenile salmon injury studies in urban estuaries such as Elliott Bay and Commencement Bay have demonstrated the susceptibility of juvenile salmonids, such as chum and chinook, to the following contaminants: polycyclic aromatic hydrocarbons (PAHs), polychlorinatede biphenyls (PCBs), hexachlorobutadiene (HCBD), hexachlorobenzene (HCB), DDTs, heptachlor, chlorinated hydrocarbons (CHs), and several pesticides. Recent laboratory investigations have demonstrated that such contaminant exposure poses the risk of impairing growth and immunocompetence levels of these juvenile salmon, and increasing mortality following pathogen exposure (Collier et al. 1998; Stein et al. 1995; Varanasi et al. 1993; McCain et al. 1990). These findings magnify the importance of isolating and capping such contaminants both for the future sustainability of salmonids and the marine mammals, birds, fish and humans that ingest marine animals in the marine food web.

Beneficial Uses

Beneficial use is the use of dredged material for human or environmental purposes that are intended to provide environmental or other benefits above and beyond simple disposal.

Beneficial use projects can occur when dredging to meet navigation purposes can provide dredged materials appropriate for meeting habitat restoration, landfilling, and construction needs. Environmental (habitat, beach nourishment) projects that involve beneficial use of dredged material require considerably more stringent criteria, such as lack of contamination and sediment structure, than projects designated for non-aquatic engineering purposes.

Although beneficial use projects have often led to counterproductive, or at a minimum unanticipated or unsustainable, results (such as the Caspian tern colony occupying the dredge material disposal site at Rice Island, Columbia River estuary, that imposes significant predation pressure on juvenile Pacific salmon migrating through the estuary) uncontaminated dredged material can provide the means to replace, albeit artificially, natural sedimentation processes that have been significantly degraded. For instance, properly designed and monitored placement of dredge materials in estuarine and nearshore marine environments can offer a wide range of benefits in terms of habitat as well as reduced dredging costs. Potential nearshore placement benefits include: supplementing the beach profile by adding material to the littoral zone and beach nourishment where natural sediment sources and shoreline drift have been impacted. This decreases nearshore wave heights, thereby reducing damage from erosive waves and storms. Similarly, fish and shellfish habitat that has been historically impacted by dredging or contamination may be rehabilitated by the deposition of uncontaminated dredged material. Practical benefits include reduced use of limited-capacity upland and offshore disposal sites, decreased mobilization/demobilization costs, and shortened haul and pumping distances.

Intertidal disposal can be applied by thin layer disposal of dredge materials to beach shores (nourishment) or used in restoration of marsh and mud/sand flat habitats that have suffered subsidence or other elevation loss Nearshore placement commonly involves the building of berms or mounds. For example, fine sediments can be used to construct stable berms in deeper waters that will diminish wave energy on land. Material closely resembling native sands on a beach can be used to build a feeder berm that will nourish nearby beaches and enhance fish habitat (USACE 1998).

Categories of beneficial use opportunities include:

- Shoreline stabilization and erosion control (fills, artificial reefs, submerged berms, etc.)
- Habitat restoration/enhancement (wetland, upland, island, and aquatic sites including use by waterfowl and other birds)
- Beach nourishment
- Capping contaminated sediments
- Parks and recreation (commercial and noncommercial)
- Agriculture, forestry, and horticulture

- Strip mine reclamation and landfill cover for solid waste management
- Construction and industrial use (including port development, airports, urban, and residential)
- Material transfer (fill, dikes, levees, parking lots, and roads)

Washington State Beneficial Use Projects

Beach Nourishment

- Point Chehalis Beach Nourishment - Objective: To protect the wastewater treatment plant and outfall line from erosion and prevent contamination of Westport's freshwater well field from overland flooding.
- Westport Breach Fill - jetty breach repair at South Beach, Westport
- Half Moon Bay Nearshore Berm - prevent shoreline erosion through feeder berms
- South Beach Nearshore Berm - prevent shoreline erosion through feeder berms
- Keystone Beach Renourishment - beach erosion renourishment
- Neah Bay Beach Restoration - beach restoration for clam production
- Quillayute Spit Renourishment - surf smelt beach nourishment and spit erosion protection

Capping

- Eagle Harbor Superfund Cap to isolate contaminated sediments
- Pier 53-55 and Pier 64/65 Caps along the Seattle waterfront to isolate contaminated sediments
- Duwamish Contained Aquatic Disposal (CAD) Site to isolate contaminated sediments
- 1976 Army Corps of Engineers Waterways Experiment Station to monitor for PCB-contaminated material
- Denny Way Sediment Cap to isolate contaminated sediments

Habitat Creation/Enhancement Projects

- Jetty Island - creation of an island with a public beach and diverse wildlife habitat that includes a protected intertidal bay
- Oak Bay Clam Habitat Enhancement - to enhance adjacent clam beds
- Bird Islands - Oregon and Washington coastal islands created totally or partially by dredged material for nesting water birds
- LaConner Marina Benches - to create benches for eelgrass plantings

Construction and Land Creation

- Milwaukee Fill - to dispose and cap contaminated sediments
- Terminal 90/91 - to create increased upland area and dispose of contaminated material
- Everett Upstream Rehandling Site - to provide materials for upland construction and beneficial uses
- Swinomish Channel Preloading - to provide material for upland development

Despite the promise of beneficial uses of dredged material, considerably more evaluation is required to assess and substantiate the ecological benefits. There is likely a greater incidence of situations where dredged materials and design were not appropriate than those that were. Problems are created by factors: such as sediment porosity, erosion potential, or sediment contamination. For instance, the use of dredged material for salt marsh creation has not been universally encouraging (Streever 2000) and some design approaches, such as planting of vegetation, has not been productive (Dawe et al. 2000). Priority should be transferred from the economics of dredging to the appropriate needs of habitat restoration, rehabilitation, and enhancement.

Dredging Biological Effects

Dredging can potentially pose risks of direct and long-term biological effects. These potential effects are diagramed in Figure 7.

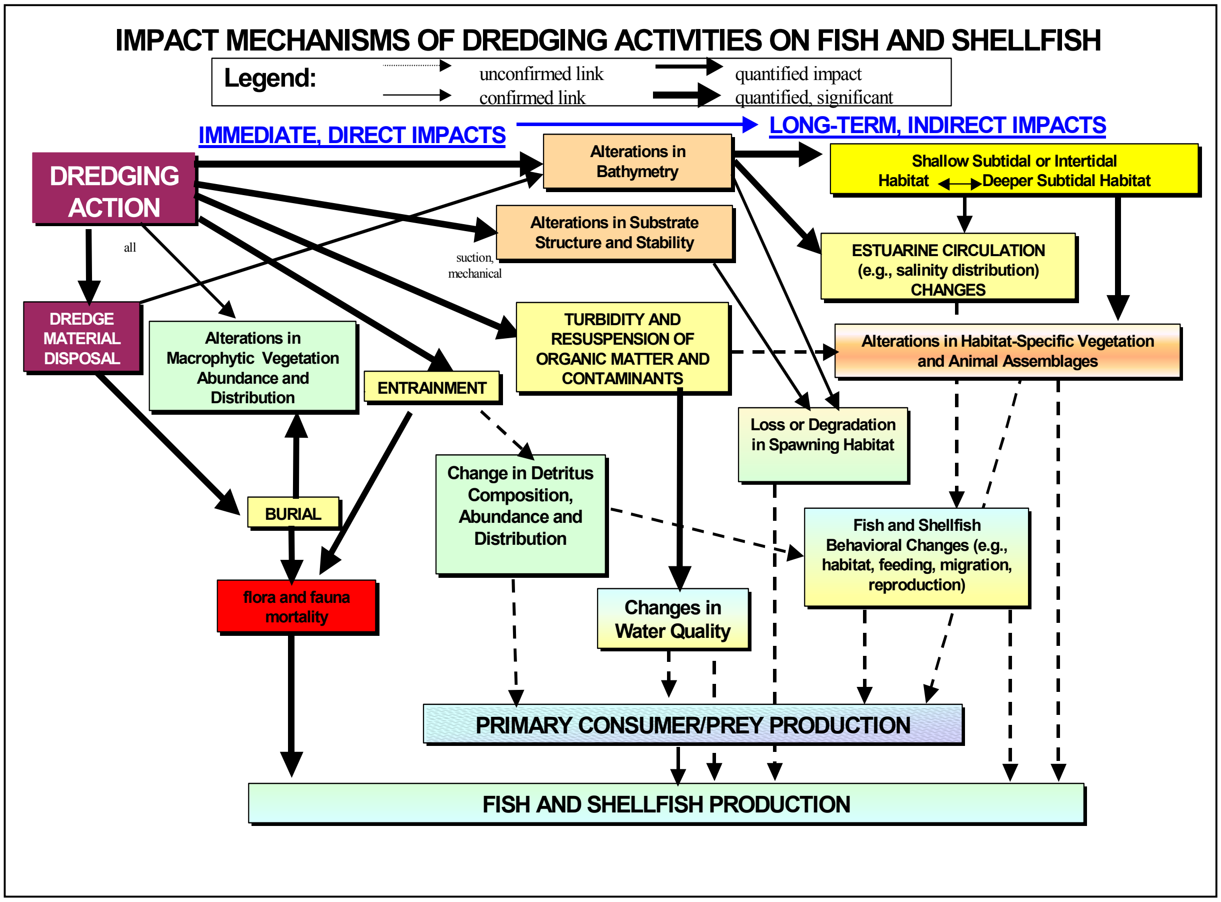

Figure7. Potential Direct and Indirect Mechanisms of Impact on Fish and Shellfish Production Attributable to Dredging Activities in Estuarine and Marine Ecosystems

Entrainment

Entrainment is the direct uptake of aquatic organisms by the suction field generated by hydraulic dredges (Reine and Clarke 1998). Entrainment occurs when an organism is trapped in the uptake of sediments and water being removed by dredging machinery (Reine and Clarke 1998). Benthic infauna are particularly vulnerable to being entrained by dredging uptake, but mobile epibenthic and demersal organisms such as burrowing shrimp, crabs, and fish can be susceptible to entrainment. Entrainment rates are usually described by the number of organisms entrained per cubic yard of sediment dredged (Armstrong et al 1981).

Dungeness Crab Entrainment

Table 11 provides a summary of Dungeness crab entrainment studies in Grays Harbor Washington and the Columbia River. These studies of Dungeness crab in the Grays Harbor area have found entrainment to be a function of the type of dredge used. Those factors influencing entrainment have been identified to include bottom depth, hopper dredge speed or cutterhead rates of advance, flow-field velocities at the drag or cutterhead, the volume of dredged material, and the direction of dredging in relation to the tidal flow. Spatial and temporal variables such as location along the navigation channel and seasonal timing of dredging operations can also combine and influence crab mortality rates. Comparing the losses to historical Washington coast crab landings, Armstrong et al. (1987) predicted that entrainment findings could reflect a potential harvestable loss ranging from 0.7% to 8.6%, depending on the disposal techniques employed. However, this prediction is tenuous and predicated on assumptions about natural and fishery mortality of adults (Armstrong et al. 1987). See also Section 7.5, discussion of Environmental Windows.

Table 11. Dungeness Crab Entrainment Studies in Grays Harbor and the Columbia River

Source	Dredge	Study Date	Location	Entrainment Rate (Crabs/Cy)
Tegelberg and Arthur 1977	Hopper	Mar 1975	Middle and outer estuary	0.131-0.327
	Hopper	Mar 1975	Outer estuary	0.449
Stevens 1981	Clamshell	Oct-Dec 1978	Middle estuary	0.012
	Hopper	Nov-Dec 1978	Outer estuary	0.233
	Pipeline	Sep-Dec 1979	Outer estuary	0.243
		Nov-Dec 1979	Inner harbor	0.0017
	Hopper	Mar 1979	Outer estuary	0.182
Armstrong, Stevens, and Hoeman 1982	Hopper	Jun 1980	Inner harbor	0.079
		Aug 1980	Middle estuary	0.107
		May-Sep 1980	Middle estuary	0.075
Armstrong, Stevens, and Hoeman 1987	Hopper	Oct 1985	Outer estuary	0.046
Dinnel, Armstrong, and Dumbauld 1986	Hopper	Oct 1985	Outer estuary	0.118
Dinnel et al. 1986	Hopper	Aug 1986	Outer estuary	0.135
				0.592
			Middle estuary	0.088
McGraw et al 1988	Hopper	Aug 1986	Outer estuary	0.155
				0.500
				0.079
			Middle estuary	0.058
Dumbauld et al, 1988	Hopper	Aug 1987	Outer estuary	0.222
				0.397
				0.133
				0.224
			Outer estuary (Bar)	9.367
Larson and Patterson 1989	Hopper	Apr-Oct 1985	Mouth of Columbia River	10.78 (0.04)[a]
		Apr-Oct 1986		1.12 (0.08)[a]
		Apr-Oct 1987		3.54 (0.18)[a]
		Apr-Oct 1988		0.32 (0.03)[a]
Wainwright et al. 1990	Hopper	Aug 1989	Outer estuary	0.220
				0.325
				0.115
				0.260
				0.40

[a]Adult crabs only
(Reine and Clark 1998)

The hopper and pipeline dredges have shown higher entrainment rates than mechanical dredges because the hydraulic dredges create a strong suction field from which organisms cannot escape (Reine and Clarke 1998). Dungeness crabs have been found to be particularly susceptible to hopper dredging with a mean rate for adult entrainment of 0.040 to .592 crabs/cy while juvenile young-of-the-year entrainment rates were found to lie between 0.32 to 10.78 crabs/cy. Pipeline dredging showed an entrainment rate of 0.243 crabs/cy and clamshell dredging showed the lowest entrainment rates. Stevens (1981) attributed the low rate of the clamshell to the combination of crabs seeking to avoid the suspended sediments and the low-frequency vibrations accompanying the lowering of the bucket into the water. Entrainment of males was found to be twice that of the females. Entrainment does not necessarily result in mortality. Hopper dredge mortality from entrainment ranged with increasing crab size from 5% mortality for 7 to 10mm crabs to 86% mortality for crabs over 75mm. For all sizes, clamshell dredges were found to have 10% mortality (Stevens 1981). Pipeline dredges were found to have 100% mortality when discharged directly into a Confined Disposal Facility (CDF)(Armstrong et al 1987). Table 12 depicts post entrainment mortality of Dungeness crab. Testing of a crab excluder mounted on the draghead of a hopper dredge found that a 25% reduction in young-of-the-year (YOY) crab entrainment could result from use of the excluder device (Shaw unpub).

Table 12. Post-entrainment Mortality Rates for Dungeness Crab by Age, Season and Dredge Type

Dredge Type	Age-class	Season	Size range (mm)	Mortality (%)
Hopper	0+	Apr – May	7-10	5
		Jun – Sep	11-30	10
		Oct – Dec	31-40	20
		Jan- Mar	41-50	40
	1+	Apr-Sep	51-75	60
		Oct-Mar	>75	86
	>1+	All	>75	86
Clamshell	All	All	All	10
Pipeline	All	All	All	100

(Wainwright et al. 1992)

Fish Entrainment

Demersal fish, such as sand lance, sculpins, and pricklebacks are most likely to have the highest rates of entrainment as they reside on or in the bottom substrates with life-history strategies of burrowing or hiding in the bottom substrate. Table 13 presents study results identifying fish species entrainment (Larson and Moehl 1990; McGraw and Armstrong 1990). McGraw and Armstrong (1992) collected entrainment information on 28 species over a 10-year period and Larson and Moehl collected information over a 4-year period. Armstrong et al. (1981) found that larger fish were not necessarily able to avoid the hopper dredge, with the largest specimen being a 234 mm tomcod. Tests of excluders mounted on the draghead of a hopper dredge showed 66%

fewer fishes (mostly flatfish and gunnels in the study) entrained through use of the device (Shaw unpub).

Table 13. Mean Fish Entrainment for Hydraulic Dredges

Species	Hopper [1] (fish/cy)	Hopper [2] (fish/cy)	Pipeline [2] (fish/cy)
Anchovy (*Engrauliidae)*	0.008	0.001	–
Northern Anchovy (*Engraulis mordax*)	–	0.018	–
Herring (*Clupeiformes*)	0.008	–	–
Arrowtooth Flounder (*Atheresthes stomias*)	–	0.008-0.022	–
Starry flounder (*Platichthys stellatus*)	–	0.001-0.002	–
English Sole (*Pleuronectes vetulus*)	–	0.006-0.035	0.001-0.003
Sand Sole (*Psettichthys metanostictus*)	–	0.001-0.016	–
Slender Sole (*Lyopsetta exilis*)	–	0.001	–
Pacific Sanddab (*Citharichthys sordidus*)	–	0.004-0.076	–
Speckled Sanddab (*Citharichthys sordidus*)	–	0.003	–
Flatfish (*Pleuronectiformes*)	0.008	0.001-0.028	–
Buffalo Sculpin (*Enophrys bison*)	–	0.006	–
Prickly Sculpin (*Cottus asper*)	–	0.020	0.004
Pacific Staghorn Sculpin (*Leptocottus armatus*)	0.003	0.007-0.092	0.001-0.037
Cabezon (*Scorpaenichthys mavmoratus*)	<0.001	–	–
Kelp Greenling (*Hexagrammos decagrammus*)	–	0.001	–
Lingcod (*Ophiodon elongatus*)	–	0.001-0.002	–
Poacher (*Agonidae*)	.009	–	–
Warty Pacher (*Occella verrucosa*)	–	0.009	–
Snailfish (*Cyclopteridae*)	–	0.001	–
Showy Snailfish (*Liparis pulchellue*)	0.002	–	–
Pacific Sandfish (*Trichodon trichodon*)	<0.001	0.002	–
Pacific Sand Lance (*Ammodytes hexapterus*)	0.341	0.036-0.594	–
Saddleback Gunnel (*Pholis omata*)	–	0.001-0.005	0.023
Snake Prickleback (*Lumpenus sagitta*)	–	0.003-0.135	–
Surfperch (*Embiotocidae*)	<0.001	0.001	–
Eulachon (*Thaleichthys pacificus*)	0.002	–	–
Chum Salmon (*Oncorhynchus keta*)	–	–	0.008
Smelt (*Osmeridae*)	–	0.009	–
Pipefish (*Syngnathus leptorhynchus*)	–	0.008	–
Bay Pipefish (*Synthidae*)	–	0.006	–
Three-Spined Stickleback (*Gasterosteus aculeatus)*	–	–	0.004
Big Skate (*Raja binoculata*)	<0.001	–	–
Longnose Skate (*Raja rhina*)	–	0.003	–
Pacific Tomcod (*Microgadus proximus*)	<0.001	0.001-0.008	–
Spint Dog fish (*Squalus acanthias*)	<0.001	–	–

Adapted from Larson and Moehl 1990 and McGraw and Armstrong 1990

Anadromous Fish

McCabe (1997) reports that white sturgeon are susceptible to dredge disposal entrainment due to their small size, limited swimming ability, and tendency to orient with bottom habitats. This makes them easily entrained or buried during disposal activities. Similarly, these same characteristics would likely make them easily entrained during dredging activities. Buell (1992) found entrainment of juvenile white sturgeon (300 to 500mm) attributed to dredging in a location known as the local "sturgeon hole". The rate of entrainment for sturgeon was 0.015 fish/cy. In Canada, juvenile salmonids and eulachons were the dominant entrained taxa due to the dredge location in a constricted waterway making it more difficult for salmonids to avoid the dredge operation (McGraw and Armstrong 1990; Larson and Moehl 1990). Simenstad (1990) reported a consensus amongst scientists that in the case of salmonids, juvenile migration would be more vulnerable to disruption than adult migration. Quinn (1988) identified an extraordinary ability on the part of salmonids to detect and distinguish turbidity and other water quality gradients. However, the cues and threshold levels triggering fish to deviate from their natural behavior are presently unknown factors. Given the state of the knowledge concerning how such environmental cues may act as stimuli that shape fish behavioral responses during downstream migration, we are unable to construct a descriptive model of the juvenile salmon response to a dredging plume (Simenstad 1990).

Shrimp Entrainment

The sand shrimp (*Crangon* spp.) is an important prey for many estuarine organisms, including Dungeness crabs, sturgeon, and salmon (Armstrong et al. 1981). During the Dungeness studies in Grays Harbor, Armstrong et al. (1981) found sand shrimp to be the organism entrained in the highest abundances with entrainment rates between 0.063 to 3.38 shrimp/cy. Table 14 presents the mean sand shrimp entrainment rates during different dredge operations. When pumps were run while the draghead or cutterhead, the highest entrainment rates occurred when the draghead or cutterhead was not in direct contact with the substrate. In contrast, when the draghead or cutterhead were position at or near the bottom, the mean entrainment rate was at the lower end of the scale at .069 shrimp/cy (Reine and Clarke 1998). Based on an annual shrimp population of 80 million, Armstrong et al. (1982) estimate that a typical dredging project in the Grays Harbor area could cause a loss to the *Crangon spp* population of 1.2 to 6.5%. Use of an excluder device showed 69% fewer shrimp entrained when utilizing the device (Shaw unpub)

Bivalve Entrainment

Entrained bivalve larvae, such as larval oysters, are assumed to suffer 100% mortality by sediment smothering, anoxia, starvation or desiccation even without direct mechanical impacts from pumping. Concern for oyster larvae entrainment in Chesapeake Bay, resulted in the development of a population model using conservative temporal and spatial distributions. Using the model, entrainment was found to have minimal negative effect on the population as the entrainment rate was calculated to range between 0.005 and 0.3% of the local population. Lunz (1985) concluded this represented no significant impact due to the dredge entraining only a very small fraction of the total water volume flowing past the dredge. Similar to larval fish, larval oysters suffer a high natural mortality rate (99.99967%) which makes the entrainment influence insignificant by comparison.

Table 14. Mean Entrainment Rates for *Crangon* spp.

Location	Dredge Type	Total cy	Entrainment Rate	
			Unadjusted	Adjusted [a]
Inner harbor (Summer)	Pipeline	357.0	3.404	-
Outer Estuary (Winter/Spring)	Pipeline	934.5	0.001	-
Middle estuary	Hopper	196.9	0.342	0.124
Middle estuary	Hopper	76.3	0.063	0.079
Middle estuary	Hopper	273.2	0.252	0.109
Inner harbor	Hopper	36.2	3.375	2.344
Middle estuary and inner estuary	Hopper	309.4	0.877	0.280
Outer estuary	Hopper	312.9	0.260	0.232

[a] Two entrainment rates are given for the hopper dredge. Certain estimates of entrainment were based on relatively small samples of dredged sediment. Samples of less than 10 cy frequently had no shrimp entrained. Unadjusted entrainment values are based on all samples regardless of total yards involved. Adjusted rates are based on these samples in excess of 10 cy (Armstrong, Stevens, and Hoeman 1982).

Adapted from Armstrong et al. 1981

Behavior Effects

Suspended sediments released into the water column by dredging activities can affect fish and other organisms in various ways. The effects include interference with breathing, feeding and predator-prey relationships.

Turbidity and Suspended Sediments

Turbidity is an optical property of water. It is that property of the water causing light to be scattered and absorbed. Turbidity is caused by a mixture of water molecules, dissolved substances, and suspended matter. The ability of a particle to scatter light depends upon the size, shape, and relative refractive index of the particular particle and the light wavelength. Turbidity is not only a measure of the amount of sediments that may be suspended in the water at any one time but a product of volume, background water conditions, and sediment type (Thackston and Palermo 1998).

Turbidity Sources

Turbidity occurs when particulates, organic and inorganic, become suspended in the water column. Through the processes of reflection, refraction, and absorption, this suspension of solids in the water column scatters light wavelengths and reduces light available to underwater environments. Total suspended solids (TSS or SS) include inorganic solids, such as clay, silt, and sand, as well as, organic solids such as algae and detritus. As a measure of dry weight of suspended solids per unit volume of water, it is reported in milligrams per liter (mg/L).

Turbidity is a natural characteristic of estuarine habitats. It is a product of estuarine and marine primary production levels combined with the effects of tidal flows, currents, storms, and the receipt of sediments and organic particulates from uplands and freshwater drainages. Suspended sediments, organic and inorganic, are an integral part of the estuarine and coastal habitat. Marine waters can be divided into two broad categories: green coastal waters and blue oceanic waters (Morel and Smith 1974). The characteristic green color of coastal and inland estuarine water is due to the absorption of shorter wavelengths by plant pigments and dissolved organic and inorganic particulates in the water. Due to this high level of particulates, estuarine and coastal waters often exhibit a 56 percent transmittance of surface light. In contrast, the clearest oceanic waters have a maximum transmittance of 98.2 percent (Jerlov 1976). This light quality in estuarine waters is also depth dependent with the lowest length, ultraviolet (UV) wavelengths found only at shallow depths and longer wavelengths found in deeper waters. Novales-Flamarique and Hawryshyn (1993) found the estuarine waters off southern Vancouver Island to have a transmission of UV wavelengths as low as 300nm at depths of 3 meters but only as low as 400 nm wavelengths at depths of 12 meters. Natural conditions, such as spring high flows from freshwater streams and flood and ebb tides, increase sediment loads and sediment re-suspension. High stream run-off periods can induce highly turbid conditions with suspended sediment concentrations of >100 mgL^{-1}. The life-history strategies of many larval and juvenile fishes, including salmonids, have evolved in response to these natural conditions (Birtwell et al. 1987; Dunford 1975; Levy and Northcote 1982; Gregory 1990). The physiological adaptations salmonids undergo as they make their transition to estuarine waters include changes in visual acuity reflecting visual adaptation to the light environment of estuarine waters. The spectral sensitivity of their vision physiology changes from the yellow and red wavelengths of freshwater systems to the green wavelengths of turbid estuarine systems paralleling their migration to estuarine waters.

Turbidity temporarily increases at varying levels near operating dredges. The levels of turbidity at any one site are a function of a combination of factors that include substrates, currents, and operational parameters. Table 15 reports a variety of suspended sediments (SS) measurements associated with different dredge types and substrates (LaSalle 1990). Table 16 describes turbidity generation across varying sediment and dredge types based on Nakai's (1978) concept of turbidity generation. Nakai's basic equation to compute the rate of sediment mass is: M=(V)(TGU)(R74/Ro) where M= mass rate of released sediment (kg/sec); TGU = turbidity generation unit (kg/cu/m); V= volume rate of dredging (cu m/sec); Ro= fraction of dredged sediment that has a critical resuspension velocity greater than the ambient current velocity, and R74= fraction of dredged sediment that has a diameter less than 0.074 mm. Table 17 displays critical resuspension velocities of different sized substrates calculated by Nakai (1978). Table 18 summarizes turbidity sources and characteristics by dredge type (LaSalle 1990). These are general guidance levels and do not reflect site-specific levels.

As the studies reflect, turbidity or suspended sediment concentrations vary throughout the water column with larger plumes typically occurring at the bottom closer to the actual dredging action and plume sizes decreasing exponentially as you move away from the dredging site both vertically and horizontally. The differences between the water column impacts of the closed bucket versus the open bucket dredges deserve further analysis in order to assess the trade-offs involved in using a tightly sealed bucket for excavating contaminated sediments at the potential cost of producing a larger plume near the bottom.

Table 15. Suspended Sediments by Dredge and Substrate Type

Dredge Type	Location	Substrate Type	Affected Plume Area	Suspended Sediment (SS) in (mg/L)
Bucket Dredge	San Francisco, CA		300 m -surface 450m- bottom	▪ At 50 m SS=<200 av. 30-90 above background levels
	Thames River Estuary, CT	Fine grains, sands and silts	300 m surface 500 m bottom	▪ SS=68 surface; SS=110 mid-depth (3m); SS=168 at near bottom (10m). ▪ SS decreased to 5 within 300m at surface and 500 m at bottom. ▪ SS adjacent to dredge = 200-400 with maximum SS within 300 m and approaching background levels at 700m
	St. John River, FL	Silts	300 m surface 450m near bottom	▪ SS=106 surface; SS=134 bottom ▪ Closed bucket reduced SS in upper water column by 56% by increased SS in lower water column by 70%.
Cutterhead Dredge	James River, VA	Clay		▪ SS=282 above background; SS>100 in lower water column; SS=av. 11.5 for upper water column; SS=37.5 for flood/ebb tides
	Savannah River, GA	Silts		▪ SS <200 above background within 480m in lower water column; SS <100 m in middle; SS=50 in upper water column
Hopper Dredge		Silty clay		▪ Behind dredge: SS=65-210 surface; SS=33-64 mid-depth (5 m); SS=58-743 bottom (10m) ▪ 50m from dredge: SS=43-45 surface; SS=46-55 at mid depth; 337 at bottom
	Grays Harbor, WA	Silty clay	60m x 1100m overflow plume=60m x 1200m Near bottom plume >120m x 2600m	▪ SS=70 max with no overflow ▪ SS=857 at 30 m behind dredge with overflow ▪ SS= 891@ 30m and 460 @ 60m behind dredge

Adapted from LaSalle 1990

Table 16. Turbidity Generation Unit Values

Type of Dredge	Power or Bucket Volume	Dredged Materials			TGU kg/cu m
		d < 0.074 mm %	d < 0.005 mm %	Classification	
Hydraulic Cutterhead	4,000 hp	99.00	40.0	Silty clay	5.3
	4,000 hp	98.5	36.0	Silty clay	22.5
	4,000 hp	99.0	47.5	Clay	36.4
	4,000 hp	31.8	11.4	Sandy loam	1.4
	4,000 hp	69.2	35.4	Clay	45.2
	4,000 hp	74.5	50.5	Sandy loam	12.1
	2,500 hp	94.4	34.5	Silty clay	9.9
	2,000 hp	3.0	3.0	Sand	0.2
	2,000 hp	2.5	1.5	Sand	0.3
	2,000 hp	8.0	2.0	Sand	0.1
Hopper	Two at 2,400 hp each	92.0	20.7	Silty clay loam	7.1
	1,800 hp	83.2	33.4	Silt	25.2
Mechanical grab	8 cu m	58.0	34.6	Silty clay	69.0
	4 cu m	54.8	41.2	Clay	84.2
	3 cu m	45.0	3.5	Silty loam	15.8
	3 cu m	62.0	5.5	Silty loam	11.9
	3 cu m	87.5	6.0	Silty loam	17.1
Mechanical bucket		10.2	1.5	Sand	17.6
		12.7	12.5	Sandy loam	55.8

(Nakai 1978)

Table 17. Critical Resuspension Velocity

Soil Type	Particle Size mm	Critical Resuspension Velocity cm/sec
Clay	0.005	0.03
Silt	0.005-0.074	0.03-7.0
Fine sand	0.074-0.42	7.0-15.0
Rough Sand	0.42-2.0	15.0-35.0

(Nakai 1978)

Table 18. Turbidity by Dredge Type

Dredge Type	Bucket	Hydraulic Cutterhead	Hopper	Agitation
Turbidity Sources	▪ Impact and withdrawal of bucket from bottom	▪ Action of rotating cutter directly related to the type and quantity of material removed and/or disturbed but not picked up.	▪ Due to draghead contact with sediment.	.
	▪ Material washing from the top and sides of bucket while it moves through the water column		▪ Overflow of sediment-laden water to increase sediment solids load	▪ Turbidity levels primarily determined by sediment type and turbulence of mixing
	▪ Spillage from bucket after breaking the water's surface			
	▪ Spillage during barge loading or intentional overloading to increase barge's effective load			
SS Levels	▪ Plume: 300m at surface and 500m at bottom. Maximum SS <500 mg L^{-1} w/i 100m	▪ SS restricted to immediate vicinity of cutterhead w/little suspension in surface	▪ Plume may be 1200m long as the dredge is mobile and w/o overflow a plume not encountered at surface or midi-depth levels.	▪ Turbidity restricted to near bottom with concentrations ranging from 180-2580 mg L^{-1} at the bottom.
		▪ Max SS w/i 3m from cutterhead. SS at bottom hundreds of mg L^{-1} yet undetectable at surface. Higher currents suspend material higher in water column	▪ Highest SS near hopper overflow.	

Adapted from LaSalle 1990

LaSalle (1990) reports that suspended concentrations in surface and bottom waters are highest (as high as 2.5 times that of other dredges) for bucket dredges due to: 1) sediment suspension from the bucket's impact to the bottom and the withdrawal of the bucket from the bottom; 2) material washing from the tops and sides of the bucket as it passes through the water column; 3) sediment spillage as it breaks the water's surface; 4) spillage of material during barge loading, or 5) intentional overflow in an attempt to increase the barge's effective load. In contrast, suspended sediment levels around a typical cutterhead dredge are likely restricted to the immediate area of the cutterhead with little suspension in surface waters (Huston and Huston 1976; Markey and Putnam 1976; Smith et al. 1976; Sustar et al. 1976; Barnard 1978; Koba 1984; Koba and Shiba 1983; Kuo et al. 1985; LaSalle 1990). Similarly, the turbidity source of a hopper dredge operation (exclusive of overflow) is at the draghead point of contact with the sediments with little, if any, plume at the surface (Hayes et al. 1984).

Fish Gill Injury

Although juveniles of many fish species thrive in rivers and estuaries with naturally high concentrations of suspended sediments (SS), studies have shown that the size and shape of SS as well as the duration of exposure can be important factors in assessing risks posed to salmonid populations (McLeay et al. 1987; Servizi and Martens 1987,1991; Murphy et al. 1989, Northcote and Larkin 1989; Newcombe and MacDonald 1991). Lake and Hinch (1999) found concentrations in excess of 40,000 mg/L to elicit stress responses (e.g. decreased leukocrit) to correlate to occurrences of gill damage. Sediment shape has also been linked with deleterious effects; with angular sediments being associated with higher fish stress responses at lower sediment concentrations. It is thought that this may be due to irritation caused by angular sediments that result in increased mucus production and decreased oxygen transfer. Although the causes of mortality were not clear, Lake and Hinch (1999) found that mortality occurred at concentrations of 100,000 mg/L with no differences found in mortality rates in natural or more angular anthropogenically derived sediments. The two studies conducted bioassays using suspended anthropogenically originated sediments, one with Arctic grayling (*Thymallus acticus*)(McLeay et al. 1987) and one with coho salmon (*Oncorhynchus kisutch*) (Lake and Hinch 1999). Both found 20% mortality at a concentration of 100 g/L in natural and angular sediments. Lake and Hinch (1999) concluded that particle angularity might not be a main factor responsible for lethality in juvenile fishes.

In concentrations of >4,000 mg/L, fish gills revealed erosion at the end of gill filament tips from both round and angular sediments. Gills of live fish were not observed to be clogged with suspended sediments. However, gills of dead fish appeared to be clogged with suspended sediments. Martens and Servizi (1993) found juvenile coho exposed to natural Fraser River suspended sediments for a period of 96 hours at concentrations of 16,000-41,000 mg/L showing an average of 1500 sediment particles lodged into gill epithelia with all such particles being of irregular and angular shapes.

Suspended sediment tolerance may be the net result of a combination of physical and physiological factors related to oxygen availability. Studies on a variety of fishes including sockeye and chinook exposed to volcanic ash (Newcomb and Flagg 1983), coho (Noggle 1978), and four-spine stickleback (*Apeltes quadracus*), cunner (*tautogolabrus adspersus*), and sheepshead minnow (*Cyprinodon variegatus*) attributed acute mortality in suspended sediment mixtures to be related to reduced oxygen uptake. Fish must keep the gills clear for oxygen exchange. In the presence of high loads of suspended sediment, they engage a cough reflex to perform that function. Due to increased metabolic oxygen demand with increased temperatures and the need to keep pathways free of sediments for oxygen uptake, increased temperature and reduced oxygen levels combine to reduce the ability of fish to cough and maintain ventilation rates. Such cumulative stressors are thought to be likely contributors to mortality during extended durations of exposure to high levels of suspended sediment (Servizi and Martens 1991).

Turbidity Behavioral Effects on Fishes

As dredging plumes may differ in scope, timing, duration, and intensity from natural conditions, it is important to assess the risks to fishes by a variety of criteria. Criteria for risk assessment include: 1) predicting plume spatial and temporal dynamics, 2) identifying thresholds of tolerance for particular species at different life-history stages, and 3) predicting the probability of populations encountering dredge plumes that exceed their tolerance levels.

As they are visual feeders, light has tremendous importance in the life of larval and juvenile fishes, including salmonids. Light conditions determine their ability to school, signal the presence of potential predators, set a background against which feeding relationships develop, and provide migration orientation. Their light perception is dependent upon the combined light reception capacity of the waters coupled with their respective visual capacities.

The matches found between the spectral sensitivities of fish species and the spectral measurements of the waters in which they are located are believed to demonstrate their adaptation to those environmental spectral conditions. The smoltification process salmonids undergo in transition from fresh to salt waters is tied to hormone levels regulating their developmental process with their adjustment to visual acuity in estuarine waters being part of their smoltification process (Beatty 1965, Folmar and Dickhoff 1981). Tribble (2000) and Britt (2001) report similar visual acuity development in larval and juvenile fishes such as sand lance, kelp greenling, and lingcod in Washington waters near Friday Harbor. Britt (2001) reported a match between the green spectral characteristics of the local waters with the spectral sensitivity of juvenile kelp greenling and lingcod. Tribble (2000) reported a similar development in the juvenile sand lance.

Sigler et al. (1988) reports that suspended sediments have been shown to affect fish functions such as avoidance responses, territoriality, and feeding and homing behavior. Similarly, Wildish and Power (1985) reported avoidance of suspended sediments by rainbow smelt and Atlantic herring to be at 20 mg/L and 10 mg/L respectively. Berg and Northcote (1985) reported short-term pulses of sediments to trigger changes in social organization of coho salmon with the return to lower turbidities allowing for the re-establishment of previous social organization. However, it also appears that some turbidity may trigger a sense of predation cover for salmonids. The studies of Gregory and Northcote (1993) demonstrate that at particular levels of increased turbidity, juvenile salmon actually increase their feeding rates while at certain threshold levels, such as >200 mg/L, they demonstrated pronounced behavioral changes in prey reaction and predator avoidance. Salo et al. (1977) in a study of dredging impacts to juvenile chum in Hood

Canal found that juvenile chum also showed avoidance reactions to particular levels of turbidity. These behavioral thresholds vary across species and life history stages. Consistent with their early reliance upon nearshore estuarine habitats with relatively high turbidities compared to pelagic or freshwater habitats, juvenile chum are classified as turbidity tolerant compared to other fishes.

It is yet unknown what behavioral mechanisms are triggered as various fish species encounter patches of increased turbidity, such as dredging plumes, in their otherwise naturally turbid waters to which they are accustomed. It is unknown what threshold of turbidity might exist that serves as a cue to fish to avoid light reducing turbidity. Simenstad (1990) describes the behavioral effects that would impact migrating fishes, such as reduced foraging success, increased risk of predation, and migration delay to be highly dependent upon duration of exposure. The primary determinant of risk level is likely to lie in the spatial and temporal overlap between the area of elevated turbidity, the degree of turbidity elevation, the occurrence of fish, and the options available to the fish relative to carrying out the critical function of their present life-history stage. For example, dredging operations in the center of a channel concentrated at depth will likely have an insignificant effect on migrating juveniles compared to operations with plumes running from bank to bank or for long distances along the shoreline. Dredging operations in the center of a channel are also less likely to significantly effect pelagic fishes due to options available for fishes in open waters.

The results of Britt (2001), Britt et al. (2001), Tribble 2000, and Ali (1975) indicate the importance of light transmission to the fitness and survival of larval and juvenile estuarine fish. Responses of estuarine and anadromous fish eggs and larvae and adults to suspended sediment concentrations are illustrated in Figure 8. Identifying vision light thresholds of native estuarine fishes at varying life history stages, the location of those fish at particular life-history stages, the spectral transmission capacity of regional waters, and predicting the location, size, turbidity level, and duration of an expected plume will help identify risks posed by dredging plumes.

Although the physics of turbidity generation can be calculated, adequate data does not exist to quantify the biological response in terms of threshold sediment dosages and exposure durations that can be tolerated by various marine and estuarine organisms. Numerical modeling simulations of dredging-related suspended-sediment plume dynamics presently being developed under the Dredging Operations and Environmental Research Program need to be correlated with field and laboratory studies further identifying information needs on specific organisms. Present data indicates that responses to suspended sediments are highly species-specific with some species having lethal effects at several hundred mg/L in 24 hours and others having no effect at concentrations above 10,000 mg/L for 7 days. Studies on east coast species have identified lethal SS concentration levels (see Figure 7) and Newcombe and Jensen (1996) have developed a predictive model for defining lethal and sublethal fish injury threshold levels for SS concentrations. However, threshold studies for the temporary impacts of suspended sediment levels specific to dredging in northwest marine environments are lacking.

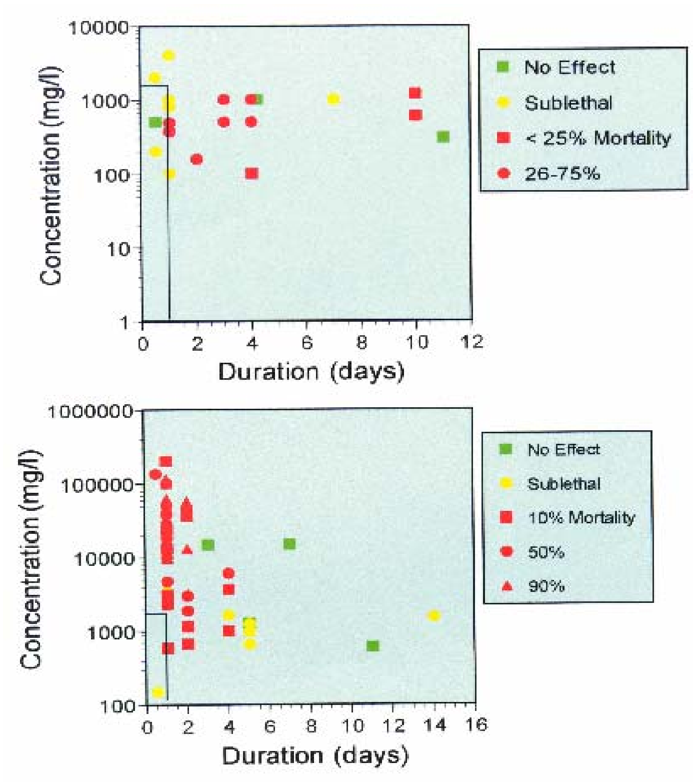

Figure 8. Responses of Estuarine and Anadromous Fish eggs and Larvae (top) and Adults(bottom) to Suspended Sediment Concentrations.
Area within the rectangles depicts a probable dosage range associated with most dredging operations (Sherk et al. 1974)

In studies of coho behavior in the presence of short-term pulses of suspended sediment, Berg and Northcote (1985) found that territorial, gill flaring, and feeding behaviors were disrupted in the presence of higher turbidity levels. In these studies, turbidity levels were measured using nephelometric turbidity units (NTU's). NTU's reflect turbidity by measuring the degree to which the particle suspension reflects light. At higher levels of turbidities such as 30-60 NTU's social organization broke down, gill flaring occurred more frequently and only after a return to turbidity of 1-20 NTU's was the social organization re-established. Similarly, feeding success has been found to be linked to turbidity levels with the higher turbidity levels reducing prey capture success. It has been established that the final phase of salmon homing migration requires olfactory cues (Hasler et al. 1978), returning chinook. Whitman et al. (1982) found in studies of returning chinook spawners that suspended ash at concentrations of 650 mg/ L did not influence homing performance. Preference experiments indicated that chinook when given the choice preferred clean home water to city water with the presence of ash reducing the preference for home water. It was concluded that fish could recognize home water despite the ash suspension and that any reduced home-water preference was due to ash avoidance Whitman et al. (1982).

Fish Larvae

Larval fish have little or no swimming capacity to employ in order to avoid dredge risks and their presence in a dredge area could pose a risk to their population. However, it is unknown how they would be impacted. Larval fish undergo very high mortality rates with a large part of that mortality being due to starvation. High fecundity levels and large larval populations are thought to offset this period of high mortality. Larval fish are visual feeders so reductions in light could further diminish their already limited prey catching capacities.

Turbidity Effects on Shellfish

Thresholds for lethal effects on clams and eastern oysters have been reported with negative impacts to eastern oyster (*Crassostrea virginica*) egg development occurring at 188 mg/L of silt (Cake 1983) compared to a 1,000 mg/L threshold for hard clam (*Mercenaria mercenaria*) eggs (Mullholland 1984). Suspended solids concentrations of <750 mg/L allowed for continued larval development. But higher concentrations for durations of 10-12 days showed lethal effects for both clams and oysters. For bivalves, when suspended-sediment concentrations rise above their filtering capacities, their food becomes diluted (Widdows et al. 1979). Clarke and Wilber (2000) report that the addition of silt, in relatively low concentrations, in environments with high algal concentrations showed increased growth on the part of mussels (*Mytilus edulis*) (Kiorboe et al. 1981), surf clams (*Spisula subtruncata*) (Mohlenberg, and Kiorboe 1981), and eastern oysters (Urban and Langdon 1984). Bricelj and Malouf (1984) found that hard clams decreased their algal ingestion with increased sediment loads. However, no growth rate differences were observed between clams exposed to algal diets alone and clams with added sediment loads (Bricelj et al. 1984). Urban and Kirchman (1992) reported similar ambiguous findings concerning suspended clay. Suspended clay (20mg/L) interfered with juvenile eastern oysters to ingestion of algae, but it did not reduce the overall amount of algae ingested. Grant and Thorpe (1991) reported enhanced summer growth of European oysters (*Ostrea edulis*) at low levels of sediment resuspension and inhibited growth with increased sediment deposition. It was hypothesized that the chlorophyll in suspended sediments may act as a food supplement that could enhance growth but higher levels may dilute planktonic food resources, thereby, suppressing food ingestion. Changes in behavior in response to sediment loads were also noted for soft-shelled clams (*Mya arenaria*) under sediment loads of 100 to 200 mg/L with changes in their siphon and mantles over time (Grant and Thorpe 1991).

Dissolved Oxygen

Based on a model assuming that remobilized and suspended sediments are anoxic, it is hypothesized that through the process of oxidation dissolved oxygen levels would be reduced in the surrounding waters. Thus dredging would appear to pose a risk of dissolved oxygen reduction. However, evidence does not support this notion. Lunz et al. (1988) reported measured dissolved oxygen levels at a Hudson River dredge site to be reduced by <0.2 mg/L. Similarly, other studies report minimal or no measurable DO reduction around dredge operations. Lunz and LaSalle (1986) reported a "worst case" DO reduction to be no more than 0.1 mg/L even with suspended sediment loads as high as 500 mg/L. Any dissolved oxygen reduction resulting from the suspension of sediments would be a function of the amount of material placed into the water column, the oxygen demand of the sediment, and the duration of the suspension. Taken in the context of the limited spatial extent of dredging turbidity plumes and the limited duration of potential impacts, dissolved oxygen reduction, if any, would be on a very limited scale as the above referenced studies demonstrate. Very little evidence exists of dissolved oxygen reduction levels associated with dredging that would pose a risk to fish moving through the immediate area. The temporary problem of increased turbidity and suspended solids can be worse where there are existing background low levels of dissolved oxygen prior to dredging, such as in estuarine systems which have more freshwater (Armstrong 1987).

For the purposes of risk assessment, the most relevant questions appear to be: 1) to what extent spatially and temporally do these impacts occur and 2) what are the options available for fish to avoid the impact. Simenstad (1990) reports that the lack of significance of dredge plumes being implicated in conditions of reduced DO is likely due to the fact that high sediment biological oxygen demand (BOD) is not common. This is contrary to the underlying assumption in the model that dredging would likely reduce dissolved oxygen levels. Table 19 presents study findings of measured DO reductions taken at dredge sites.

Table 19. Dissolved Oxygen (DO) Measurements at Dredge Sites

Location	Dredge	DO Reductions	References
New York-Hudson River	Bucket	<0.2mg L^{-1} in lower water column.	Lunz et al. 1988; Houston et al. 1990
Grays Harbor	Cutterhead	reduced by 2.9 mg L^{-1} (periodic reductions)	Smith et al. 1976
Oregon tidal slough	Hopper	reduced by 1.5-3.5 mg L^{-1} during slack tide in lower water column and increase by 2 mg L^{-1} with flood tide	USACE 1982
Coos Bay, OR	Hopper	minimal to no change	Slotta et al. 1973

Noise

Noise Effects

It has been documented that noise can influence fish behavior. Fish detect and respond to sound utilizing its cues to hunt for prey, avoid predators and for social interaction (Hawkins 1986; Fay 1988; Kalmijn 1988; Cox et al. 1987; Myrberg 1972; Myrberg and Riggio 1985; Wisby et al. 1964; Nelson 1965; Nelson et al 1969; Richard 1968). In a paper reviewing the application of several sensory signals in the interests of controlling and modifying fish behavior, Popper and Carlson (1998) reported that although sonic, infrasonic and ultrasonic ranges are potentially useful for controlling fish behavior, most experiments testing the usefulness of such sounds have provided ambiguous results. They also found the effects of noise to be highly dependent upon the flow field in which the noise occurs.

Feist (1991, Feist et al. 1992) found that based upon the known range of salmonid hearing, underwater noise from pile-driving would be expected to be heard by salmonids within a radius of least 600m from the noise source. Throughout the study of pile-driving effects on juvenile pink and chum salmon at Everett Homeport, Feist (1991) found pile-driving operations to affect the distribution and behavior of fish schools around the site. The presence of fish schools during non-pile driving days was two-fold compared to periods when pile driving active. Feist (1992) reported that although it was conceivable that pile-driving noise was audible to juvenile salmon from over 600 meters from the source, the perceived relevance of that signal to the fish couldn't be assessed without further research concerning salmonid audition. Moore and Newman (1956) reported that the classic fright response of salmonids to sound was the "startle" or "start" behavior. Blaxter (1981) found Atlantic herring to show an avoidance response to sound stimuli and Schwarz and Greer (1984) found similar responses on the part of Pacific herring. Sound has been shown to affect growth rates, fat stores, and reproduction (Meier and Horseman 1977; Banner and Hyatt 1973). High intensity sounds can also permanently damage fish hearing (Popper and Clark 1976; Enger 1981; Cox et al 1987). It is possible that auditory masking and habituation to loud continuous noise from machinery may decrease detection by salmonids of approaching predators (Feist 1991; Feist et al.1992). Dredging operations can be continuous around the clock and over long periods of time. The level of alteration to ambient noise levels is dependent upon the equipment used. It is possible that pile driving consists of more intense bursts of sound energy than dredging produces. Further research into the effects of noises specific to dredging are required to conclude the effects dredging noises may have upon salmonids and other fishes. The duration and level of sound alteration in the presence of sensitive species are important factors to consider in predicting ecological effects.

Environmental Windows

Environmental windows are used to constrain dredging and disposal operations to specific activity timeframes in order to protect sensitive biological resources and their habitats from detrimental effects. Environmental windows can be defined as the time period that is left over after all the temporal environmental restrictions are mapped onto the calendar (NRC Environmental Windows for Dredging Workshop 2001). Environmental windows have been used to avoid dredging effects in this country for over 30 years, and it is estimated that over 80% of the USACE dredging projects are subject to such windows. While often considered an effective management tool, arguments still persist about the applicability of dredging environmental windows given the advances and improvements in existing dredging and dredged material placement technology and operations (Averett 2001). In addition to the issue of technological and operational advances in dredging, Grigalunas et al. (2001) cites other disadvantages of environmental windows. These disadvantages include: (1) the effect of dredging environmental windows in extending the length of the overall dredging period and increasing impacts to species of lesser economic or regulatory interest, but not necessarily of lesser ecological importance, whose critical period coincides with the dredging environmental window; (2) the length of the dredged material disposal period being extended by dredging environmental windows with a delayed recovery of fishery resources at the disposal sites, and (3) along with both the obvious and hidden costs due to the project and local economy. On the other hand, it is possible that a window incorporating every species concern may not leave enough time to complete dredging projects.

In the Pacific Northwest, environmental windows are used to protect important life history stages of fish, birds, crab, and marine mammals. Although protecting juveniles and adults of important commercial and sport fish species from direct impact due to dredge-induced turbidity is the most common reason for dredging environmental window restrictions, protecting a variety of life-history stages has also been a focus of resource agencies. Given that many fish species deposit demersal eggs, increased mortalities due to both smothering by sedimentation and clogging and damage of gill tissues by suspended sediments are of concern. Incorporation of information on spawning and migration timing, larval drift transport, and egg and larval locations for specific estuarine and marine species that has accumulated over the past 30 years can protect vulnerable species during those periods of sensitive life-history stages at locations where they are known to aggregate.

By segregating dredging impacts by life-history stages, mechanisms of impacts can be considered in relation to specific organisms and life-history strategies. For example, impact analysis could include: effects to juveniles and adults *in situ*, firstly by entrainment and secondly by exposure to turbidity plumes; effects to juvenile and adult organisms migrating through the region, and effects to larval and other life-history stages that lack motility and the capacity to avoid turbidity and sedimentation effects. Crustaceans, such as crabs and shrimp, sessile molluscs, such as clams and oysters, and drifting larvae may be highly susceptible to the dredging effects of entrainment and turbidity as they are unable to avoid dredge equipment and the plume. Presently, the level of information available suggests that impacts are both spatial and temporal for specific species, but does not conclusively support specific dredging windows without further analysis. Further analysis for more site- and species-specific environmental windows is required to enhance animal protection from negative effects dredging effects.

Environmental windows typically tend to constrain dredging operations during critical spring and summer months that would coincide with migration, spawning and nesting activities. However, as Tables 3, 5, 7, and 8 illustrate, some organisms use habitats impacted by dredging activities for critical life-history stages at varying times throughout the year (Reine et al. 1998). This seasonal and region-wide variation in habitat use requires environmental windows that are site specific. It is recommended that specific procedures or conditions of operation be applied on a project-by-project basis with fish windows and construction timing restrictions evaluated on a project specific basis. Project evaluation based upon site location and features, such as sediment composition, plant and animal assemblages, and timing of the seasonal and migration patterns of effected organisms can more effectively protect the ecosystems specific to the seasonal and annual variations and characteristics of that site (NRC 2001).

Long-Term Effects

Potential long-term effects of dredging include detrimental responses of biota to changes in habitat, water quality, and other conditions that are delayed and usually occur after the actual dredging activity. For instance, contaminant mobilization, contaminant leaching, bioaccumulation, and trophic transfer through the food web can result during the dredging or disposal of contaminate sediments but may not be immediately manifested in exposed biota. Long-term effects also include the cumulative effects of landscape-scale alterations of estuarine/marine bathymetry and habitat structure that include the overall scope of dredging activities undertaken in the region. Understanding the scope of current dredging activities requires a breakdown and comparison of the areal extent of maintenance dredging undertaken annually compared to new project dredging and the extent this dredging alters the nature of existing habitats (e.g., shallow subtidal to deeper subtidal or intertidal to shallow subtidal). An analysis of the scope and nature of current dredging activities can lay the groundwork for assessing the long-term cumulative effects that dredging activities can pose to existing estuarine and marine dynamics and the effects such changes may have on a variety of marine species.

Contaminated Sediments

Contaminated sediments are of particular concern due to the risk of contaminant transport and exposure posed to aquatic organisms and humans through bioaccumulation and biomagnification in the marine food web. These risks can also be passed on to humans through that food web. Once contaminants are present in the system, processes that pose risks of contaminant transport include natural and anthropogenic aquatic disturbances such as storms, spills, bioturbation by animals, vessel prop wash, and dredging-related activities.

In the DMMP process, dredging projects are ranked high, moderate, low-moderate, or low based on the known or suspected presence of chemicals of concern. Ranking dictates the amount of testing needed to characterize a dredging prism adequately. Chemicals of concern include: guaiacol and chlorinated guaiacols, tri-, tetra-, and pentachlorobutadienes, polychlorinated dibenzodioxins (PCDDs) and dibensofurans (PCDFs), butyltins, and TBT. See Appendix A for an extensive listing of chemicals of concern. For each dredge project, pre-project sampling and testing is undertaken. These steps include screening for the presence and concentrations of chemicals of concern. Based on those results, the required level of further biologic testing and evaluation is then determined. Once appropriate characterization information has been obtained, dredged material disposal and beneficial use options are determined. Further information on the DMMP process may be obtained from the User Manual accessible at http://www.news.usace.army.mil/dmmo/. Dredging and disposal of contaminated sediments may also be accomplished via cleanup authorities such as the State of Washington Model toxic Control Act (MTCA), the federal Comprehensive Environmental Response Compensation and Liability Act (CERCLA), and the federal Resource Conservation and Recovery Act (RCRA). A bibliography of contaminated sediment and disposal information sources can be found in Appendix C of this document.

Biologic Contaminant Uptake Processes

Bioaccumulation refers to contaminant uptake from water or dietary sources. It refers to the accumulated concentration of a contaminant in consumer tissue upon its passage through two or more trophic levels. This transport of contaminants between multiple trophic levels (i.e. prey to predator) (Swartz and Lee 1980) is called trophic transfer. Different contaminants have different levels in their potential for biomagnification. Trophic transfer coefficient (TTC) is the contaminant concentration in consumer tissue divided by contaminant concentration in the food sources. Both arsenic and cadmium are examples of contaminants that biomagnify in marine food webs. Figure 9 graphs TTC of various organic contaminant compounds in the marine food web and Figure 10 graphs TTC of trace metals.

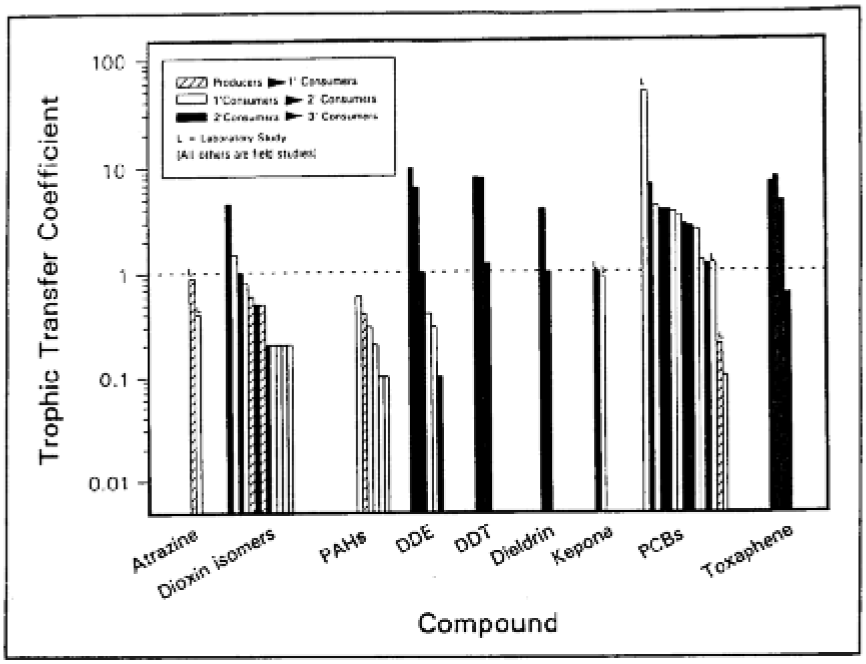

Figure 9. TCC for Organic Compounds
TCC>1 indicates a potential to biomagnify in aquatic food webs
(USACE 1995)

Management of Contaminated Sediments

The Army Corps of Engineers is responsible for maintaining navigable waterways, and also regulates dredging activities under the Clean Water Act. In Washington State, the management of dredging and disposal pursuant to the Clean Water Act is accomplished through an interagency approach that includes ACOE, Seattle District; EPA, Region 10; Washington Department of Ecology (DOE), and the Washington Department of Natural Resources. This cooperative management is the Dredged Material Management Program (DMMP). Three separate programs are combined under the DMMP: the Puget Sound Dredged Disposal Analysis (PSDDA), Grays Harbor and Willapa Bay, and the Lower Columbia River programs. The Columbia River jurisdiction is shared with ACOE, Portland District. There exists an extensive body of literature on the subject of contaminated sediments, disposal, and transport mechanisms in the marine environment. This paper contains a separate bibliography and access to database links to extensive literature on this topic.

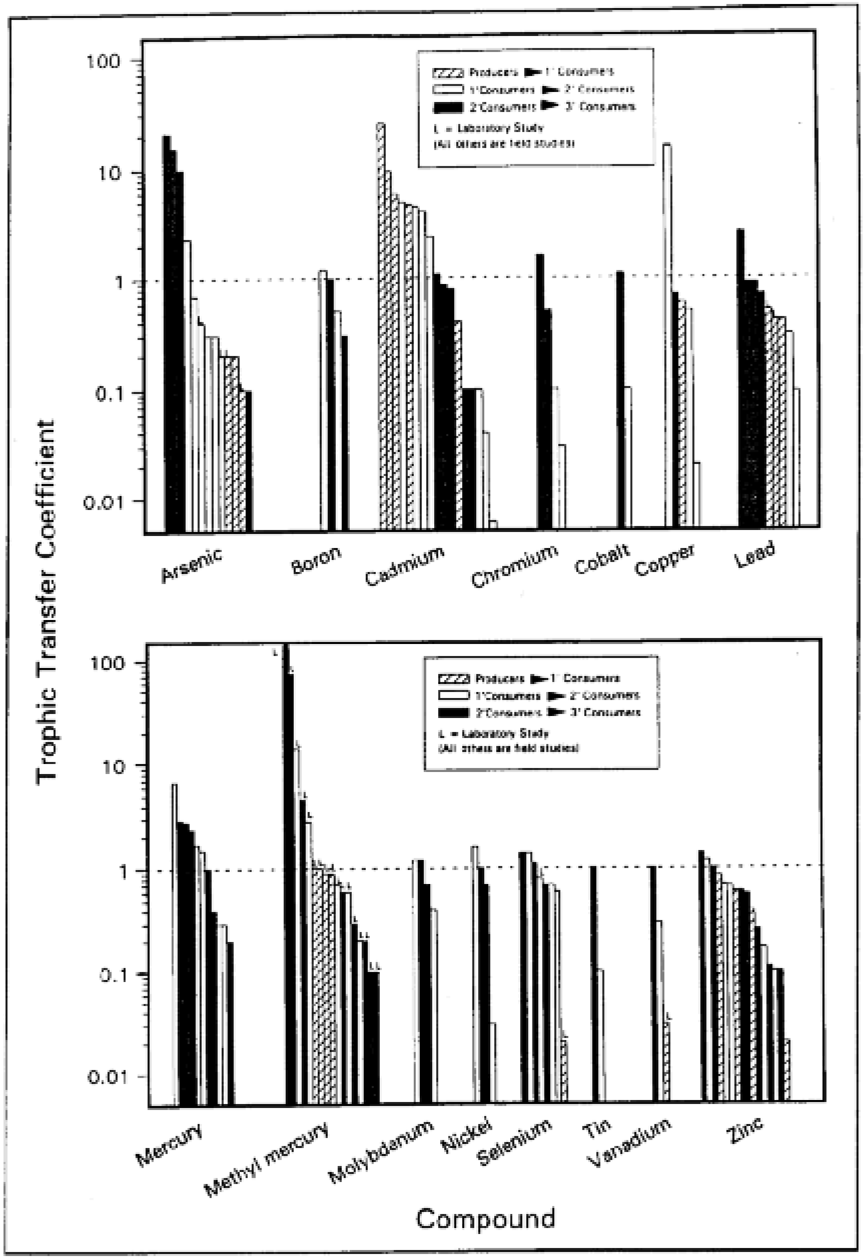

Figure 10. TCC for Metals in Aquatic Food Webs. A TCC of >1 indicates a potential for biomagnification in marine food webs (USACE 1995)

Priority Habitat Alterations

Defining Priority Habitats

The shoreline landscape, including the intertidal and subtidal zones, backshore and adjacent components of the terrestrial landscape (e.g., cliffs, snags, mature trees, dunes, meadows) that contribute to shoreline biologic functions (e.g., sand/rock/log recruitment, nutrient contribution, and erosion control) provide important habitats supporting breeding, rearing, and migration functions for many marine species. Important landscape substrates include: consolidated substrate, such as rocky outcroppings in the intertidal and subtidal marine/estuarine environment consisting of rocks greater that 25 cm (10 in) diameter; hardpan, and/or bedrock and unconsolidated substrates consisting of rocks less than 25 cm (10 in) diameter; gravel, shell, sand, and/or mud, and vegetated intertidal and subtidal habitats.

In general habitats supporting the breeding, rearing, and migration functions of important species are referred to as critical or priority habitats. Habitat identified by WDFW as priority habitats have one or more of the following characteristics (WDFW 2001a; 2001b):

- Breeding
- Rearing
- Migration
- Supports high densities and diversities of fish and wildlife
- Vulnerable to alterations
- Limited availability

Washington Department of Fish and Wildlife identification of priority habitat include the following habitats as priority habitats (WDFW 2001b).

- **Vegetated marine habitats -** eelgrass meadows, kelp beds, and turf algae in the intertidal and subtidal to a depth of approx. 30.5 m (100 ft) below mean lower, low water (MLLW). These are priority habitats due to the comparatively high fish and wildlife densities and diversities characteristic of them and the vulnerability of such habitats to loss due to changes in substrate, wave energy, sedimentation, nutrient levels, and bathymetrics.

- **Backshore and adjacent terrestrial landscape -** cliffs, snags, mature trees, dunes, meadows that are important to shoreline associated fish and wildlife and that contribute to shoreline function (e.g., sand/rock/log recruitment, nutrient contribution, erosion control). Consolidated Substrate: Rocky outcroppings in the intertidal and subtidal marine/estuarine environment consisting of rocks greater than 25 cm (10 in) diameter, hardpan, and/or bedrock. Unconsolidated Substrate: Substrata in the intertidal and subtidal marine environment consisting of rocks less than 25 cm (10 in) diameter, gravel, shell, sand, and/or mud.

- **Deepwater tidal habitats and adjacent tidal wetlands -** these habitats are usually semi-enclosed by land but with open, partly obstructed or sporadic access to the open ocean, and in which ocean water is at least occasionally diluted by freshwater runoff from the land. The salinity may be periodically increased above that of the open ocean by evaporation. Along some low-energy coastlines there is appreciable dilution of seawater. Estuarine habitat extends upstream and landward to where ocean-derived salts measure less than 0.5% during the period of average annual low flow. Includes both estuaries and lagoons.

Large-Scale Landscape/Ecosystem Impacts

For both rural and industrialized urban estuaries, the action of sediment removal (and consequently the removal of plants and animals associated with the sediments) removes not only some level of productivity from the system but also alters to some (typically undocumented) degree the habitat structure and ecosystem processes that pervade the estuarine landscape beyond the local influence of the dredging or dredged material disposal site. This paper presents conceptual tools to identify the criteria for assessing the potential impacts of removing, through dredging and disposal, a measured amount of productivity into a conceptual framework for identifying and enhancing an impacted landscape. The approach of this paper expands estuarine functions to encompass not only productivity, but also continuity, complexity and diversity, and interconnectivity with the objective of protecting or building those functions back into a given landscape area. It assumes that urban industrialized landscapes have high levels of previous impacts and that rural environments have a lesser level of previous impacts. Primary to identifying the effects of impacts and the direction to build functional complexity back into the system is the identification of estuarine functions.

This paper separates estuarine functions into the following general categories:

- Productivity of diverse primary, secondary, and tertiary producers
- Complexity and diversity of habitats
- Interconnectivity representing a natural continuum along estuarine, energy, and other gradients
- Other landscape and ecosystem-scale attributes that maintain population resilience

For the purpose of assessment, the functions provided by estuarine and nearshore marine landscapes for fishes and motile macroinvertebrates can be categorized as ***capacity***, ***opportunity***, and ***realized functions*** (Simenstad and Cordell, 2000).

Capacity includes those habitat attributes that promote foraging, growth, and growth efficiency. These include decreased mortality rates and ultimately together promote the production and survival of juvenile salmon and other fish and shellfish. Productivity and availability of prey resources are examples of *capacity*. ***Opportunity*** characterizes the ability of fish, such as juvenile salmon, to access and benefit from the habitat's capacity. Tidal elevation and the extent of important geomorphic features, such as edges of tidal channels, are examples of *opportunity*. ***Realized function*** represents the net cumulative effect of animal responses contributing to fish occupying a given habitat. Survival is the ultimate measure of *realized function, which* is related to the metrics of habitat-specific residence time, foraging success, and growth (Simenstad 2000a). This paper approaches long-term effects from a landscape ecology approach with the goal of facilitating the identification of critical regions in a given estuarine or marine landscape area and better identify critical habitat functions and the changes associated with dredging that could affect the *realized functions* of those habitats.

Because estuarine ecological functions are determined by diverse and dynamic interacting physiochemical processes and landscape elements, the resulting landscape is complex and diverse in composition, distribution, and organization of biota and is characterized by a high level of habitat connectivity supporting viable fish populations (Simenstad 2000b).

The concept of landscape ecology employs the following three fundamental definitions of landscape elements found in Forman and Godron (1986) and Turner (1989):

- **Patches** - nonlinear homogeneous areas differing from the surrounding matrix. Such areas are characterized by shape, type, heterogeneity, and boundary characteristics (i.e. edges).

- **Matrix** - surrounding area is different from embedded patches. This is the most extensive connected element in the landscape and controls landscape dynamics and function. In industrial landscapes, developed land- forms constitute the matrix.

- **Corridors** - narrow strips of land or water that differ from the matrix and may connect two or more patches.

In the case of urban industrialized estuarine landscapes, dredging alterations to bathymetry, salinity, and productivity usually occur against a background of collective impacts to the system occurring over many decades. Over the last several decades, much of the dredging in urban areas has resulted from the requirement to maintain existing channel and berth depths or to deepen existing dredged areas to accommodate larger vessels. In the case of rural or less developed areas, the dredging activities are likely occurring against a background of impacts of lesser magnitude and different in character. For example, conversion of intertidal habitat to subtidal habitat and alteration of channel bathymetry can affect productivity and critical habitat in a given system. In order to absorb such changes and avoid a net loss of productivity, compensation without net less would require a valuation process that includes productivity compensation for recolonization time and compensation that is either in-kind to what was lost or an addition of higher value. For example, the landscape ecology approach could require the exchange to also include the element of habitat continuity, which could go beyond the immediate site location and treat that site within the context of a larger habitat area. An important part of the landscape approach is identifying existing habitats and needs in the estuary and establishing criteria for prioritizing enhancement efforts on an estuary-wide basis. Table 20 shows a NRDA ranking of restoration sites involving potential disposal of contaminated sediments in the Puyallup River Delta and Commencement Bay. H=high, M=medium, L=low, and N=no effect. These rankings were used to evaluate site contributions to important natural landscape processes and features.

Table 20. Natural Resources Damage Assessment (NRDA) Restoration Site Contribution Assessment

Site	Restore Tidal-Freshwater	Expand Osmoregulatory Transition	Build on Natural "Neodelta"	Enhance Habitat Connectivity	Restore Natural Delta Edges and Channels	Link to Natural Uplands and Drainages
Wasser-Winter	L	M	N	L	L	L
Hylebos Conservancy Area	N	L	N	L	L	H
Meaker Beach Marsh	N	L	N	M	M	M?
Middle Waterway Shore	N	L	M	L	M	N
Tahoma Salt Marsh	N	N	N	L	M	L?
Hylebos Conservancy Area	N	L	N	M	M	M?
DNR Marine View Drive Reserves 1-3	N	N	N	M	M	H
Slip 5	N	N	L	M	H	N
Gog-Le-Hi-Le	M	H	N	H	N	L
Swan Creek	H	M	N	M	N	H?
Dickman Mill Shore Park	N	N	N	L	H	L?
Olympic View	N	L	M	H	H	N
Olympic View Beach	N	L	M	H	H	N
Clear Creek Slough	H	M	N	M	N	H?
Milwaukee Waterway	N	L	H	H	M	N
Milwaukee Waterway w/natural connector channel	N	M	H	H	M	N
St. Paul Cap	N	L	H	M	L	N

Simenstad 2000a

Dredge Induced Habitat Conversions

Conversion of Shallow Subtidal to Deeper Subtidal

Maintenance dredging, which is by far the most frequent form of dredging in Washington State, converts shallower subtidal habitats to deeper subtidal habitats through periodic deepening to remove accumulated sediments. Depending upon site characteristics, maintenance dredging may occur annually or in intervals of 10 years or longer. These different dredging timelines likely represent different disturbance regimes both in terms of the ability of the benthos to recolonize prior to redisturbance and the magnitude of benthic productivity affected by dredging. In a literature review report on dredge and disposal effects, Morton (1977) reported the range of effects to invertebrate communities to be from negligible to severe with impacts ranging from short to long-term. The literature review reported that short-term, small-scale dredging and dredge disposal projects impacted benthic communities less than long-term, large scale projects.

McCabe and Hinton (1998) reported assessment of the standing crops of benthic invertebrates, particularly the gammarid amphipods (*corophium* spp.), in the Columbia River to be one of the most important means of determining the habitat values of various areas for fishes, including migrating juvenile salmonids, as C*orophium salmonis* were found to the dominant prey for juvenile salmonids. It is also an important prey for juvenile white sturgeon (*Acipenser transmontanus*) in the lower Columbia River at the Bonneville Dam (Muir and Emmett 1988).

In a pre- and post-dredging study of dredge effects on benthic invertebrates and sediment characteristics in the Whakiakum County Ferry Channel (River Mile 43.2), McCabe et al. (1996) reported that no significant effect of the clamshell dredging project on the standing crops of benthic invertebrates were detected. He concluded that apparently, benthic invertebrates in the dredged area were able to recolonize the area quite rapidly after dredging. Similarly, a study on dredging effects to benthic macroinvertebrates in a South Carolina estuary (Van Dolah et al. (1984) noted short-term effects with a substantial recovery within 3 months. In that case, the rapid recolonization was attributed to the immigration via sediments of the slumping channel walls, which were similar to the sediments removed during dredging. McCabe concluded that benthic invertebrates living in the slumping channel walls adjacent to Wahkiakum County Ferry Channel could have contributed to the rapid recolonization of the dredged area. McCabe et al. (1996) also reported that *Corophium salmonis* might have migrated into the dredged channel from areas more distant than the slumping channel walls. McCabe et al. (1996) reported that no significant effect from the channel dredge project on the *Corophium salmonis*, *Corbicula fluminea*, *Certopogonidea* (diptera) larvae or *Corophium* spp. populations. Also, no significant effects to the median grain size or percent volatile solids were detected. However, median grain size was significantly smaller in the ferry channel than in the control area. McCabe et al. (1996) concluded that this study clearly demonstrated the need for at least one control area in environmental assessments of dredging projects and the importance of conducting sampling prior to dredging in both the impacted and control areas. Recolonization of the benthos is important to those organisms dependent upon benthic habitats. In a study to evaluate the effects of dredged material disposal on biological communities, Hinton et al. (1992) reported a significant increase in benthic invertebrate densities between June 1989 (pre-disposal) and June 1990 (post-disposal). This was concluded to reflect annual variations. However, it was reported that it is probable that dumping of the dredged material adversely impacted benthic invertebrates during disposal operations and for a short time therefore. However, the benthos was found to successfully recolonize the area by June 1990. Recolonization could have occurred by invertebrates burrowing up through newly deposited sediments or recruitment from surrounding areas (Richardson et al. 1977).

Large channel deepening projects can potentially markedly alter ecological relationships through the change of freshwater inflow, tidal circulation, estuarine flushing and freshwater and saltwater mixing. Due to such changes, Miller et al (1990) reported that only through comprehensive areal surveys over a minimum of four seasons before dredging with follow-up surveys after dredging could impacts of channel deepening on aquatic resources be determined. In a dredged and undredged area comparison pertaining to maintenance dredge activities in the Port of Everett's public marina, Pentec (1991) found catches of fish to be higher in the dredged area before dredging than after dredging. Catches dropped from 89.8 fish per tow to 2.7 fish per tow and from eight species to five species.

Maintenance dredging can also be strategically designed and implemented to reduce the area of impact by employment of features such as settling basins. These are deep areas that are positioned as sediment traps in estuarine areas of high sediment bedload. Settling basins are developed upriver of accreting navigational channels, such as in the Duwamish River estuary, and a relatively small area is dredged periodically to sufficient depth to capture sediment transported down-estuary. This reduces the area being impacted from the length of the impacted navigation channel to that involving only the settling basin area; the down-estuary navigation channel rarely needs to be dredged when settling basins operate effectively and are maintained.

Conversion of Intertidal to Shallow Subtidal Habitats

New construction dredging could convert intertidal to subtidal habits. However, such conversion is infrequent in this region and is only associated with large new construction projects such as marinas. Intertidal conversions pose the risk of impacting plant and animal assemblages that are uniquely adapted to the particular light, current and substrate regimes of intertidal areas. Such conversions are described as producing a habitat "trade-off" of intertidal and shallow-subtidal communities for deeper, subtidal communities. The loss of vegetated shallow-water, nearshore habitat, given the important rearing and refugia functions such habitats provide for migrating juvenile salmon and other important fishes, would represent landscape capacity loss as well as potential disruption and reduction in landscape connectivity.

Alteration of Estuarine Circulation and Salinity Structure

Estuarine biota is most likely to be subjected to long-term shifts in critical factors such as salinity distribution. Effects may be most evident among anadromous and other (e.g. early life history stages) that are particularly sensitive to salinity, especially during transitions from fresh water to saline waters. Deepening an estuarine channel can alter the degree and form of estuarine mixing as the extent of mixing of fresh waters and salt waters in estuaries is dependent, in part, on channel bathymetry, fluvial and tidal energy, substrate roughness, and other lesser factors. Channel deepening can cause tidal waters to intrude further up the estuary, causing a change in salinity levels and, likely, a change in plant and animal communities. Because the degree of mixing will determine whether this effect is restricted to salinity regimes near the bottom of the channel, or is reflected throughout the water column, the potential impact will depend upon the factors that dominate estuarine circulation. Any change in animal communities will at least be reflected in the distribution of demersal fish and benthic and epibenthic macroinvertebrates because they may be most sensitive to the upstream extent of the salt (sometimes taking the form of a "wedge") intrusion; salinity intrusion is greatest under these stratified conditions (or during neap tides in the cases of estuaries that switch between stratified and mixed estuarine circulation patterns). While the extent of area impacted may be less in systems with high mixing (because of relatively less intrusion) the greatest impact is most likely to occur when mixing produces changes in the salinity regime at the surface because surface salinity regimes dictate to a large degree the composition of intertidal animal and plant assemblages. This is particularly the case for brackish marsh and tidal scrub-shrub and forested wetland communities because they are highly dependent upon pore-water salinity, which varies less than water column salinity, and is particularly sensitive to the position of the 0.5-5 ppt isohaline. In addition to the resident (e.g., benthic) biota that may be significantly impacted by increased salinity intrusion, more transient species such as migrating juvenile salmon may be affected by diminished freshwater-tidal and brackish habitat.

While biota in estuarine channels under-going maintenance dredging may accommodate periodic small changes in salinity intrusion, the response of estuarine biota to major new dredging projects or significant channel deepening requires predictions of the scale of salinity intrusion change. Circulation modeling, using 3-dimensional hydrodynamic models, is the primary tool to evaluate the magnitude and extent of salinity change. Monitoring of salinity intrusion and within-habitat salinity regimes is also desirable to expand our systematic understanding of bathymetric controls on estuarine circulation that can be attributed to dredging.

Summary of Existing Guidance

Dredging activities in the estuarine and marine waters of Washington State are regulated by a variety of state and federal laws and agencies.

Federal Authority

The Clean Water Act, the Rivers and Harbors Act of 1899, and the Ocean Dumping Act define federal authority over dredging and disposal activities. Under Section 301 of the CWA the federal government prohibits the discharge of any pollutant into navigable U.S. waters unless authorized by a permit. This includes dredged materials. Under Section 404 of the CWA, the federal government has the responsibility to protect and preserve the water quality of U.S. navigable waters with the USACE having the authority to grant permits for any dredging or filling. The EPA has the authority to veto permit decisions if the discharge is determined to have an unacceptable adverse effect. Under the Rivers and Harbors Act of 1899, the federal government has the responsibility to protect and preserve the navigability of U.S. waters, and has authority over the construction of piers, breakwaters, jetties, dredging, and watercourse modification in those waters. Under this authority, such activities require a USACE permit. Under the Ocean Dumping Act, the federal government regulates the dumping of all materials into ocean waters and implements U.S. obligations under the London Dumping Convention. These include permits for the dumping of dredged materials.

Under the National Environmental Policy Act of 1969 (NEPA), any major federal action that will significantly affect the environment also requires an environmental impact statement to identify potential adverse consequences of the project. The agency is required to consider environmental consequences and alternatives, including "no action", with interagency consultation also required.

The Coastal Zone Management Act of 1972 seeks to preserve, protect, develop, and where possible, to restore and enhance the resources of the Nation's coastal zone for this and succeeding generations. It seeks to accomplish this through encouraging and assisting states in the management of coastal development through the development of state coastal zone and shoreline management plans. Washington State passed its Shoreline Management Act in 1971. Federal agencies are required to comply to the maximum extent practicable with state CZMA and shoreline management plans but they are not required to obtain a permit.

State Authority

Under the authority of Section 401 of the Clean Water Act (CWA), the state has Water Quality Certification authority to permit discharges into state waters. The purpose of the 401 Water Quality Certification is to ensure a project complies with all state laws, regulations, and rules. The state also has authority under state law RCW 75.20 to grant permits provided for under state administrative law, WAC 220-110-040, for the purpose of providing protection for all fish life through a consistent and predictable state-wide system of rules. Under this law, Hydraulic Project Approval (HPA) permits are granted for all state and local projects that meet both State Environmental Policy Act (SEPA) and HPA requirements.

The state also has authority over shoreline development under the Shoreline Management Act (WAC 173-27) and the applicable local Shoreline Master Program (jointly administered by the Department of Ecology and the local jurisdiction).

Most dredging projects are also subject to the rules of the State Environmental Policy Act (WAC 197-11) whereby review under these rules are usually incorporated into one of the permitting processes named above. In cases where a Corps action or permit is involved, review under the National Environmental Protection Act (NEPA) occurs. Under the US constitution, the federal government has sovereign immunity over state law. However, USACE does coordinate with WDFW to ensure concerns are addressed. Similarly, the state water quality agency, the Washington State Department of Ecology, includes WDFW concerns in Water Quality Certification permits.

Regulation of Disposal of Dredged Materials

In Washington State, the suitability of disposal of dredged materials in open water is coordinated under an interagency group comprised of the U.S. Army Corps of Engineers, Seattle District (Corps); U.S. Environmental Protection Agency, Region 10 (EPA); Washington Department of Ecology and Washington Department of Natural Resources (DNR). These regulatory agencies jointly administer the Dredged Material Management Program (DMMP) for three areas grouped by geographic area, consisting of Puget Sound, Grays Harbor, and Willapa Bay, and the Washington jurisdiction area of the Lower Columbia River programs. In general, new construction type dredging projects require new permits with a full review process and maintenance dredging requires periodic full review, depending upon project specifics.

The permit process begins when the project proponent submits a complete Joint Aquatic Resource Permits Application (JARPA) to the appropriate agencies. After a Public Notice and comment period pass, other applicable permits are issued such as: a Water Quality Certification, Hydraulic Project Approval, and ACOE permits under the CWA and Rivers and Harbors Act. Prior to these various permits being processed, there is a detailed review of the sediments proposed for dredging. This is called the “dredged material evaluation process”. Sediments that meet DMMP requirements and that are slated for unconfined, open water disposal at a designated open water site do not need to be approved through the Endangered Species (ESA) Section 7 process, as disposal actions at DMMP sites have been approved programmatically by USFWS and NMFS through 2004.

Under the dredged material evaluation process, the DMMP agencies determine if the sediments from the dredging project require testing. A “suitability determination” is prepared by the DMMO and signed by all agencies documenting material suitability for open water disposal. If it is determined that the sediment does *not* need to be tested then the following information is required:

- Volume of materials to be dredged;
- Disposal site to be used;
- Last sampling and testing dates;
- Application of guidelines apply to the current dredging cycle;
- Summary of previous testing data as necessary; and
- New pollution sources or known incidents (i.e., a spill) that have occurred which might impact the quality of sediment to be dredged.

If it is determined that the sediment *does* need to be tested, a "Sampling and Analysis Plan (SAP)" must be developed which characterizes the project sediments. The SAP to test sediments for a project consists of a series of steps, described as follows:

- Determine the rank of the project;

- Determine the volume of material to be dredged;

- Determine the required number of Dredged Material Management Units (DMMUs) and field samples based on the volume and rank;

- Develop a conceptual dredging plan, and

- Develop a sampling plan that distributes the DMMUs to reflect the conceptual dredging plan and allocation of the required number of field samples.

There are detailed guidelines available through the Dredged Material Management Program (DMMP) regarding each step, for further information, the users manual should be referenced and the applicable agencies should be contacted. The DMMO is the main point of contact for interagency dredged material management programs in the State of Washington. The DMMO website at http://www.nws.usace.army.mil/dmmo/homepage.htm provides access to DMMP biennial reports and Puget Sound Dredge Disposal Analysis (PSDDA) user manual and reports.

Washington State Closure Periods

Closure periods established by the Washington Department of Fish and Wildlife (WDFW) are the primary measure used to protect juvenile salmonids from the adverse effects of dredging activities. The purpose of these in-water construction closures is to limit the exposure of juveniles to unsuitable conditions. The WDFW, through the hydraulic code, enforces closures on in-water construction in marine and estuarine waters during periods when juvenile salmonids are abundant. Low numbers of juvenile salmonids may be present outside the closure periods and could be exposed to adverse conditions caused by dredging.

Note: The Washington State Shoreline Management Act and U.S. Clean Water Act Sections 401 and 404, although not detailed in the following list of guidance materials, also apply.

Hydraulic Code Rules

WAC 220-110-250 Saltwater Habitats of Special Concern

In the following saltwater habitats of special concern, or areas in close proximity with similar bed materials, specific restrictions regarding project type, design, location and timing may apply as referenced in WAC 220-110-270 through 220-110-330. The location of such habitats may be determined by a site visit. In addition, the department may consider all available information regarding the location of the following habitats of special concern.

(1) Information concerning the location of the following saltwater habitats of special concern is available on request to the habitat management division of the department of fish and wildlife. These habitats of special concern may occur in the following types of areas:

  (a) Surf smelt (*Hypomesus pretiousus*) spawning beds are located in the upper beach area in saltwater areas containing sand and/or gravel bed materials.

  (b) Pacific sand lance (*Ammodytes hexapterus*) spawning beds are located in the upper beach area in saltwater areas containing sand and/or gravel bed materials.

  (c) Rock sole (*Lepidopsetta bilineata*) spawning beds are located in the upper and middle beach area in saltwater areas containing sand and/or gravel bed materials.

  (d) Pacific herring (*Clupea harengus pallasi*) spawning beds occur in lower beach areas and shallow subtidal areas in saltwater areas. These beds include eelgrass (*Zostera spp*.) and other saltwater vegetation and/or other bed materials such as subtidal worm tubes.

  (e) Rockfish (*Sebastes* spp) settlement and nursery areas are located in kelp beds, eelgrass (*Zostera* spp) beds, other saltwater vegetation, and other bed materials.

  (f) Lingcod (*Ophiodon elongatus*) settle and nursery areas are located in beach and subtidal areas with sand, eelgrass (*Zostera* spp), subtidal worm tubes, and other bed materials.

(2) Juvenile salmonid (family salmonidae) migration corridors, and rearing and feeding areas are ubiquitous throughout shallow nearshore saltwater areas of the state.

(3) The following vegetation is found in many saltwater areas and serves essential functions in the developmental life history of fish or shellfish:

  (a) Eelgrass (*Zostera* spp.);
  (b) Kelp (Order *laminariales*);
  (c) Intertidal wetland vascular plants (except noxious weeds).

WAC 220-110-270 Common Saltwater Technical Provisions Applicable to Marine Dredging Projects

The following technical provisions apply to projects in saltwater areas. Project activities may be prohibited where project impacts adversely affect fish habitats for which no proven mitigation methods are available.

(1) Use of equipment on the beach area shall be held to a minimum and confined to specific access and work corridors.

(2) Bed material, other than material excavated for bulkhead footings or placement of bulkhead base rock, shall not be utilized for project construction or fills. The department may allow placement of dredged material in areas for beneficial uses such as beach nourishment or cleanup of contaminated sediments.

(4) Beach area depressions created during project activities shall be reshaped to preproject beach level upon project completion. Hydraulic clam harvesters shall comply with hose conditions specified in WAC 220-52-018.

(5) No debris or deleterious material shall be disposed of or abandoned waterward of the ordinary high water line except at an approved in-water site.

(7) No petroleum products or other deleterious materials shall enter surface waters.

(8) Project activities shall be conducted to minimize siltation of the beach area and bed.

(11) Project activities shall not degrade water quality to the detriment of fish life.

(12) If a fish kill occurs or fish are observed in distress, the project activity shall immediately cease and the department granting the HPA shall be notified immediately. Such fish kill events that would cause cessation of dredging activities under current WDFW technical provisions have reportedly not been observed in this region.

WAC 220-110-240 Tidal Reference Areas

(1) Tidal Reference Area 1 (Shelton): All saltwater areas in Oakland Bay and Hammersley Inlet westerly of a line projected from Hungerford Point to Arcadia.

(2) Tidal Reference Area 2 (Olympia): All saltwater areas between a line projected from Hungerford Point to Arcadia and a line projected from Johnson Point to Devil's Head. This includes Totten, Eld, Budd, Case and Henderson Inlets, and Pickering Passage.

(3) Tidal Reference Area 3 (South Puget Sound): All saltwater areas easterly and northerly of a line projected from Johnson Point to Devil's Head and southerly of the Tacoma Narrows Bridge.

(4) Tidal Reference Area 4 (Tacoma): All saltwater areas northerly of the Tacoma Narrows Bridge and southerly of a line projected true west and true east across Puget Sound from the northern tip of Vashon Island.

(5) Tidal Reference Area 5 (Seattle): All saltwater areas northerly of a line projected true west and true east across Puget Sound from the northern tip of Vashon Island and southerly of a line projected true east from Point Jefferson at 47° 15' N. latitude across Puget Sound. This area includes Port Orchard, Port Madison, and Dyes and Sinclair Inlets.

(6) Tidal Reference Area 6 (Edmonds): All saltwater areas northerly of a line projected true east from Point Jefferson at 47° 15' N. latitude across Puget Sound and southerly of a line projected true east from Possession Point to Chenault Beach and from Foulweather Bluff to Double Bluff.

(7) Tidal Reference Area 7 (Everett): All saltwater areas northerly of a line projected true east from Possession Point to Chenault Beach, easterly of a line projected 5° true from East Point to Lowell Point, and southerly of the Stanwood to Camano Island Highway. This area includes Port Gardner, Port Susan, and parts of Possession Sound and Saratoga Passage.

(8) Tidal Reference Area 8 (Yokeko Point): All saltwater area westerly and northerly of a line projected 5° true from East Point to Lowell Point, north of the Stanwood to Camano Island Highway, and easterly and southerly of Deception Pass Bridge and the Swinomish Channel Bridge on State Highway 536. This area includes Holmes Harbor, Saratoga Passage, Skagit Bay, Similk Bay, and most of the Swinomish Channel.

(9) Tidal Reference Area 9 (Blaine): All saltwater area in Skagit County and Whatcom County that lies northerly of the Swinomish Channel Bridge on State Highway 536 and westerly and northerly of Deception Pass Bridge.

(10) Tidal Reference Area 10 (Port Townsend): All saltwater area of Puget Sound as defined in WAC 220-16-210 except Hood Canal south of a line projected from Tala Point to Foulweather Bluff, and except all waters defined in Tidal Reference Areas 1 through 9. Area 10 includes waters of the San Juan Islands, Admiralty Inlet, the Strait of Juan de Fuca, and associated bays and inlets.

(11) Tidal Reference Area 11 (Union): All saltwater area of Hood Canal southerly and easterly of a line projected from Lilliwaup Bay to Dewatto Bay.

(12) Tidal Reference Area 12 (Seabeck): All saltwater areas of Hood Canal northerly of a line projected from Lilliwaup Bay to Dewatto Bay and southerly of a line projected true east from Hazel Point. This area includes Dabob Bay and Quilcene Bay.

(13) Tidal Reference Area 13 (Bangor): All saltwater area of Hood Canal northerly of a line projected true east from Hazel Point and south of a line projected from Tala Point to Foulweather Bluff. This area includes Port Gamble.

(14) Tidal Reference Area 14 (Ocean Beaches): All saltwater area between Cape Flattery and the Oregon border at the mouth of the Columbia River, excluding Grays Harbor and Willapa Bay.

(15) Tidal Reference Area 15 (Westport): All saltwater area in Grays Harbor easterly of a line projected from the outermost end of the north jetty to the outermost end of the south jetty, and westerly of 123° 59' W. longitude.

(16) Tidal Reference Area 16 (Aberdeen): All saltwater area in Grays Harbor easterly of 123° 59' W. longitude and westerly of the Union Pacific railroad bridge across the Chehalis River.

(17) Tidal Reference Area 17 (Willapa Bay): All saltwater area in Willapa Bay easterly of a line projected from Leadbetter Point to Cape Shoalwater Light.

WAC 220-110-271 Prohibited Work Times in Saltwater Areas

Work waterward of the ordinary high water line shall be prohibited or conditioned for the following times and areas. The prohibited times for the protection of migrating juvenile salmonids, surf smelt, Pacific herring spawning beds, and proposed prohibited times to protect Dungeness Crab are listed by Tidal Reference Area in Table 21.

WAC 220-110-320 Dredging in Saltwater Areas.

Dredging projects shall incorporate mitigation measures as necessary to achieve no net loss of productive capacity of fish and shellfish habitat.

The following technical provisions apply to dredging projects. In addition, these projects shall comply with technical provisions and timing restrictions in WAC 220-110-240 through 220-110-271.

(1) In addition to those timing limitations listed in WAC 220-110-271, dredge timing may be further restricted to protect other important fish life.

(2) If a fish kill occurs or fish are observed in distress, dredging shall immediately cease and the department shall be notified immediately.

(3) A hydraulic dredge shall only be operated with the intake at or below the surface of the material being removed. The intake shall only be raised a maximum of three feet above the bed for brief periods of purging or flushing the intake system.

(4) Each pass of a clamshell dredge bucket shall be complete. Stockpiling of dredged material below the ordinary high water line may be prohibited.

(5) Dredging shall be conducted with dredge types and methods that cause the least adverse impact to fish and shellfish and their habitat.

(6) Dredged bed materials shall be disposed of at approved in-water disposal sites or upland. The department may allow placement of dredged material in areas for beneficial uses such as beach nourishment or cleanup of contaminated sediments.

(7) Dredging shall be conducted to a depth not greater than the channel depth at the seaward end. Dredging to depths greater than the channel at the seaward end may be authorized only in berthing areas and turning basins for commercial shipping purposes.

(8) Dredging is prohibited in herring spawning beds and in rockfish and lingcod settlement and nursery areas.

(9) Kelp (Order laminariales) adversely impacted due to dredging shall be replaced using proven methodology.

(10) Dredging shall avoid adverse impacts to eelgrass (*Zostera spp*).

Table 21. Prohibited Work Times in Saltwater Areas to Protect Salmon, Smelt, Herring and Proposed Periods for Dungeness Crab (*proposed closed times)

Tidal Reference Area	Juvenile Salmonid Migration Feeding and Rearing Areas	Surf Smelt Spawning Beds	Herring Spawning Beds	*Dungeness Crab Spawning and Rearing
Shelton Shelton1 Shelton1 sSShelton	March15-June 14	—	January 15-March 31	
Olympia	March 15-June 14	July 1-March 31	January 15-March 31	
S.Puget Sound	March 15-June 14	October 1-April 30	January 15-March 31	
Tacoma	March 15-June 14	October 1-April 30	January 15-April 14	
Seattle	March 15-June 14	September 1-March 31 in all areas except Eagle Harbor and Sinclair Inlet. Year round in Eagle Harbor and Sinclair Inlet	January 15-April 30	
Edmonds	March 15-June 14	—	—	*June-Sept
Everett	March 15-June 14	Year round	February 1-April 14	*June-Sept
Yokeko Point	March 15-June 14	Year round	February 1-April 14	*June-Sept
Blaine	March 15-June 14	Year round	February 1-April 14: South of a line running due west from Governor's point February 1-June 14: North of a line running due west from Governor's point	
Port Townsend	March 15-June 14	Sept 15-October 31 in Kilisut Harbor; October 15-Janaury 14 in Dungeness Bay; May 1-August 31 in Twin Rivers and Deep Creek; Year round in San Juan Islands	January 15-April 30	*June-Sept
Union	March 15-June 14	September 15-March 1	January 15-March 31	
Seabeck	March 15-June 14	—	February 15-April 14	
Bangor	March 15-June 14	October 15-January 31	January 15-April 14	
Ocean Beaches	March 1-June 14	—	—	Restrict. restrict. for white sturgeon?
Westport	March 1-June 14	—	—	*May-June 30
Aberdeen	March 1-June 14	—	—	*May-June 30
Wilapa Bay	March 1-June 14	—	February 1-March 14	*May-June 30

Conclusions

Direct Biological Effects

The direct biologic effects of both maintenance and new project dredging activities include entrainment mortalities, behavioral effects, contaminant release, and noise effects that can induce behavioral change or cause injury and fitness risks. However, with the exception of contaminant exposure, these effects tend to be temporary and localized. The literature reflects that fish gill injury from exposure to high suspended sediment loads is likely the principle mechanism of injury, but to what extent is uncertain and deserves further analysis. Thresholds for gill injury specific to marine and estuarine environments have not been identified. The most relevant issue is likely the ability of fish to avoid plumes and dredge activity areas. This requires an understanding of the nature of fish present and the options available to them in order to avoid the dredge areas. We conclude that a clearer understanding of the effects of dredging on a variety of marine fishes would come from a further synthesis of what is known about the life-history strategies, water column use, and timing of a wide variety of marine fishes in specific areas. This would enable the further development of site- and species-specific environmental windows to avoid entrainment and limit risks. We conclude that refinement in the identification of injury thresholds, behavioral effects, and the distribution of species across all life-history stages are required to avoid animal injury and morality risks.

Long-Term Effects

Given the dynamic nature of estuarine and marine ecosystems, the history of freshwater and marine dredging, and the lack of long-term pre and post project monitoring and documentation of effects specific to how individual dredging projects effect the larger ecosystem make it difficult to conclusively identify effects. The lack of documentation specific to the nature and timing of recolonization preclude the ability to make conclusive statements on long-term effects. We conclude that dredging projects and the beneficial uses of dredged materials present the highest potential as an effective restoration tool when projects are planned on an ecosystem landscape-scale basis specific to the life-history needs of the biota utilizing the larger landscape.

Recommendations

The recommendations forwarded in this paper include: 1) more extensive use of multi-season pre- and post- dredge project biological surveys to assess animal community impacts; 2) incorporation of cumulative effects analysis into all dredging project plans; 3) increased use of landscape-scale planning concepts to plan for beneficial use projects most suitable to the area's landscape ecology and biotic community and food web relationships; 4) further identification of turbidity and noise thresholds to assess fish injury risks, and 5) further analysis and synthesis of the state of knowledge on what is known about the spatial and temporal distribution of fish and shellfish spawning, migration behaviors, and juvenile rearing in order to evaluate dredging environmental windows on a site-specific basis.

- Reduce the volume of material that must be dredged, and the frequency of dredging, whenever possible.
- Avoid projects and expansions that convert intertidal to subtidal habitat. If such conversion is unavoidable, employ comprehensive large-scale risk assessment to identify the cumulative effects of site-specific changes to ecosystem dynamics.
- Require that hopper dredges, scows and barges used to transport dredged materials to the disposal or transfer sites to completely contain the dredged material to minimize the extent of turbidity effects.
- For long-term projects where continuous dredging and onloading to barges occurs, require periodic movement of the barge to reduce unnecessary shading (for more information regarding shading impacts see white paper on *Over-Water Structures: Marine Issues*).
- Minimize ambient light changes caused by nighttime artificial lighting on dredging structures that may alter prey-predator relationships and increase predation risks for salmonids and other marine fishes (Prinslow et al 1979).
- Avoid dredging in known or suspected geoduck tracts. If geoducks are present, document change between pre- and post-dredge animal age and abundance.
- Incorporate cumulative effects analysis into all dredging decisions and project plans.
- Increase the use of multi-season pre-project surveys of benthos to compare with post project surveys to understand dredging impacts.

- Base turbidity threshold testing for PSDA operations upon site sediments present.

- Where applicable and involving uncontaminated sediments, consider beneficial use of dredged materials that contributes toward habitat restoration, rehabilitation and enhancement, and that incorporates a landscape ecology approach to design and implementation and involves pre- and post-disposal surveys of benthos and fish communities.

- Avoid beneficial use projects that impose unnatural habitats and features on the estuarine/marine landscape, involve habitat trade-offs or substitutions, or that significantly alter fundamental ecological processes; instead, use beneficial use projects only to restore or supplement natural habitats through the enhancement of natural (sedimentation) processes. In the case of large, potentially damaging or unproductive projects, require rigorous assessment of the assumed response of a beneficial use disposal project, such as modeling alternative designs (Srinivas and Taylor 1996)

- Clarify and improve the guidance used to evaluate contaminant bioaccumulation from dredged materials

- Utilize hydrodynamic models to predict system-wide changes in salinity and turbidity regimes for project assessment planning that avoids or minimizes impacts to estuarine and nearshore marine biota

- Technological tools such as the "Silent Inspector" should be considered whenever particularly sensitive habitats or organisms are at risk due to dredging proximal to sensitive habitats or in projects where sediments both suitable and unsuitable for unconfined open water disposal will be dredged adjacent to each other. This computerized electronic sensor system can monitor pipeline dredging operations and assist in operational documentation and regulatory compliance by providing record accessibility and clarity. It also offers advantages for planning, estimating, and managing dredging activities.

Data Gaps

- Utilize landscape-scale-planning concepts to plan for beneficial use projects most suitable to the area's landscape ecology and existing prey-predator relationships.
- Identify noise thresholds affecting fish behavior or fitness
- Further analysis and synthesis of state of knowledge on what is known about spatial and temporal distribution of fish and shellfish spawning and migration behaviors and juvenile rearing in order to evaluate dredging environmental windows on a site-specific basis.
- Identify suspended sediment thresholds to assess the fish injury risks specific to the temporary nature of dredge plumes in the marine environment. Newcombe and Jensen (1996) have developed a threshold model for risk assessment in freshwater environments that can be modified to identify thresholds in the marine environment.
- Further analysis and synthesis of knowledge is required to assess dredging risks to various marine fishes at varying life-history stages.
- Identify spatial and temporal distribution of fish and shellfish at various life-history stages to build site-specific dredging environmental windows that minimize animal injury.
- Identify cumulative thresholds associated with dredge-induced changes in salinity intrusion and other critical physiochemical processes in estuaries.
- Identify compensatory abilities of those populations potentially damaged in early life history stages.

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APPENDIX A

Estuarine and Marine Classification Definitions-Natural Heritage Program

Dominant Plant and Animal Assemblages in Washington State Marine Intertidal and Shallow Subtidal Habitats

Dominant Plant and Animal Assemblages in Washington State Estuarine Intertidal and Shallow Subtidal Habitats

Table A-1. Estuarine and Marine Classification Definitions-Natural Heritage Program

System	Subsystem	Substrate	Wave Energy	Depth
Marine	**Intertidal**	**Consolidated:** bedrock, boulder, hardpan **Unconsolidated:** cobble, mixed coarse, gravel, sand, mixed fine, mud, organic	**Exposed** **Partially Exposed** **Semi-Protected** **Protected**	**Eulittoral:** Areas between MHWS and ELWS **Backshore:** Areas above MHWS but receiving marine influence through spray or irregular flooding
Marine	**Subtidal**	**Consolidated:** bedrock, boulder, hardpan **Unconsolidated:** cobble, mixed coarse, gravel, sand, mixed fine, mud, organic	**High:** exposed to oceanic swell or very strong currents **Moderate:** exposed to only wind waves and moderate tidal currents **Low:** exposed to only very weak or no currents with little wave action	**Shallow:** 15 m or less below MLLW **Deep:** over 15m below MLLW
Estuarine	**Intertidal**	**Consolidated:** bedrock, boulder, hardpan **Unconsolidated:** cobble, mixed coarse, gravel, sand, mixed fine, mud, organic	**Open:** exposed to moderate to long fetch, windwaves and/or current **Partly Enclosed:** partially enclosed with minimal wave action **Lagoon:** Protected, largely enclosed embayment **Channel/Slough:** inlets submerged with tidal backup water at high tide	**Eulittoral:** Areas between MHWS and ELWS **Backshore:** Areas above MHWS but receiving marine influence through spray or irregular flooding
Estuarine	**Subtidal**	**Consolidated:** bedrock, boulder, hardpan **Unconsolidated:** cobble, mixed coarse, gravel, sand, mixed fine, mud, organic	**Open:** exposed to moderate to long fetch, windwaves and/or current **Partly Enclosed:** partially enclosed with minimal wave action **Lagoon:** Protected, largely enclosed embayment **Channel/Slough:** inlets submerged with tidal backup water at high tide	**Shallow:** 15 m or less below MLLW **Deep:** over 15m below MLLW

(adapted from Dethier 1990)

Table A-2. Dominant Plant and Animal Assemblages in Washington State Marine Intertidal and Shallow Subtidal Habitats

System	Substrate	Wave Energy	Plants	Fish	Shellfish
Marine Intertidal eulittoral	rock	Exposed partially exposed semi-protected	rockweed, algae, kelps, surfgrass coralline algae,	sea perch, sculpins, rockfish, cod, high cockscomb, sculpins, clingfish, prickleback	mussels, barnacles, crab, limpets, chitons
	cobble	partially exposed	algae	herring spawn, sculpins, clingfish, gunnels	barnacles, clams, crab, shrimp
	mixed-coarse	semi-protected protected	seasonal drift algae		shrimp, clams
	gravel	partially exposed	none	shiner perch, juv. tomcod Eng. sole, starry flounder, gunnels, sculpins, surf smelt spawn, sand lance larvae	amphipods, shrimp
	gravel	semi-protected	algae	shiner perch, juv. Eng. sole, flounder, sculpins	clams, crab
	sand	exposed partially exposed	none	sole, flounder, Pac. sand lance, Pac. tomcod, perch, sculpins, gunnels, sturgeon poachers, Pac. herring, surf smelt	clams, shrimp
	sand	semi-protected protected	eelgrass, algae,	sole, juv.salmonids, sculpin, surf smelt, sand lance and candlefish larvae	clams, shrimp
	mixed fines	semi-protected protected	eelgrass, algae, drift algae	juv. Pac. tomcod, lingcod, tube-snout, pipefish, perch, prickleback, gunnels, sculpin, poacher, sanddab, surf smelt, juv. Eng. sole flounder	clams, crabs, shrimp
	mud	protected	eelgrass, algae	flounder, juv. Eng. sole, tube-snout, perch, pipefish, gunnel, goby, sculpins, herring spawn	
Marine Shallow Subtidal	rock & boulders	mod to low energy	surfgrass, eelgrass, algae	greenlings, rockfish, sculpins, cabezon, gunnels, perch	crabs, scallops, chitons, abalone, snails, urchins
	gravel	high & low energy	algae	greenlings, rockfish, sculpins, cabezon, gunnels, perch, flatfish	snails
	mixed-fines	moderate to high energy	algae	juv. Eng. sole, sole, flounder, juv. Pac. tomcod, poachers, sculpins, perch	bivalves, scallops, crabs, snails, geoducks, clams

(adapted from Dethier 1990)

Table A-3. Dominant Plant and Animal Assemblages in Washington State Estuarine Intertidal and Shallow Subtidal Habitats

System	Substrate	Wave Energy	Plants	Fish	Shellfish
Estuarine Intertidal eulittoral	mixed-coarse	open	algae; often eelgrass beds lie just subtidally of these beaches	sculpins, juv. salmon, trout, blennies, gunnels, clingfish, perch, surf smelt, sole, stickleback, herring spawn	bivalves, clams, crabs, oysters, limpets
	gravel	open	ulva, algae	juv. Eng. sole, perch, cabezon, flounder sculpins, greenling, gunnels, poachers	
eulittoral & marsh	gravel	partly enclosed	pickleweed, saltwort, rockweed, sedge, martima		
open	sand	open	eelgrass, gracilaria, drift algae	juv. salmon, flounder, goby, sculpin, Eng. sole,	clams, shrimp
Estuarine Intertidal	sand mixed-fine mud	partly enclosed lagoon	vascular plants, bulrush,sedge, pickleweed (depending on salinity)	perch, juv. salmon, cutthroat, stickleback	clams, crabs
	mud	partly enclosed enclosed	eelgrass		
lagoon, marsh, backwaters	Organic sand mixed-fine mud	partly enclosed	sedge, grasses, vascular plant (depending on salinity) marsh plants,ulva, eelgrass	Pac. herring, Pac. sand lance, tube-snout, juv. Eng. sole, flounder, sculpins, stickleback, pipefish, prickleback, gunnels, surf smelt, perch, juv. salmon	shrimps, crabs, moon snails, oyster,
	mixed-fines mud	channel/slough	eelgrass, lined with marsh plants	juv. salmon, stickleback, flounder, sculpin	clams, crabs
Estuarine Shallow Subtidal	rock	open	algae		chitons, limpet, crabs, snails
	cobble	open	eelgrass		crab, clams
	mud	open	eelgrass, algae, ulva, kelp	sculpins, sole	bivalaves
	mud	partly enclosed		Pac. tomcod, flounder, sole, sculpin, smelts	bivalves, geoducks
	Sand mud	channels		Eng. sole, sanddab, sculpns, prickleback, Pac. tomcod, perch, peamouth, juv. salmon, flounder	crab, shrimp

(adapted from Dethier 1990)

APPENDIX B

Glossary of Terms

Many of the terms in this glossary are defined specifically within the context of marine dredging activities

ABIOTIC
- the non-living factors of a given area, such as temperature, wind, substrate

ACCRETION
- the slow addition of land by the deposition of water-borne sediment through the net effect of wave action and longshore drift.

ALGAE
- simple plant form having no true roots, stems or leaves; ranging in size from microscopic, single-celled plants (microalgae) to seaweeds (macroalgae)

ALLUVIUM
- unconsolidated mineral material moved by water and deposited in a fan shape at streams, river beds, floodplains, lakes, estuaries, and at the base of mountain slopes

AMPHIPOD
- crustaceans in the Order Amphipoda, of subclass Malacostraca

ANADROMOUS FISH
- species that are born in fresh water, spend a large part of their lives in the sea and return to freshwater rivers and streams to reproduce (e.g., salmon)

AQUATIC ENVIRONMENT
- the geochemical environment in which dredged material is submerged under water and remains water saturated after disposal is completed.

AQUATIC ECOSYSTEM
- bodies of water, including wetlands, that serve as the habitat for interrelated and interacting communities and populations of plants and animals.

ARTIFICIAL REEF
- an artificial made structure designed to simulate a natural reef.

ASSEMBLAGE
- the group of species generally associated with a given habitat type.

BACKSHORE
- the area wetted by storm tides but normally dry between the coastline and the high tide line. It may be a narrow gravel berm below a sea bluff or a broader complex of berms, marshes, meadows, or dunes landward of the high tide line

BARRIER BEACH
- an accretion shore form of sand and gravel that has been deposited by longshore drift in front of bluffs, bays, marshes, or estuaries, and functions like a storm barrier.

BANK
- a land surface above the ordinary high water line that adjoins a body of water

BAR
- a shore form similar to a spit or a hook, though generally not attached to the mainland during periods of high water.

BEACH
- the zone of unconsolidated material that is moved by waves, wind and tidal currents, extending landward to the coastline.

BEACH FEEDING
- a process by which beach material is deposited at one or several locations in the updrift portion of a driftway. The material is then naturally transported by a wave's down drift to stabilize or restore eroding beaches or berms

BEACH RESTORATION AND ENHANCEMENT
- the alteration of terrestrial and tidal shorelines or submerged shorelines for the purposes of stabilization, recreational enhancement, or aquatic habitat creation or restoration.

BEST AVAILABLE TECHNOLOGY
- the most effective method, technique, or product available which is generally accepted in the field, and which is demonstrated to be reliable, effective and preferably low maintenance.

BIODEGRADABLE
- materials that are capable of being readily decomposed by biological means

BAITFISH (also called prey fish)
- group of fish that are important to aquatic predators such as salmon, marine mammals and seabirds as food items. Examples of prey fish include: herring, sand lance and surfsmelt

BATHYMETRY
- the measurement of depths of water in oceans, seas, and lakes. Also, information derived

BENEFICIAL USES
- placement or use of dredged material for some productive purpose. Beneficial uses may involve either the dredged material or the placement site as the integral component of the beneficial use

BENTHIC
- pertaining to the bottom substrate or the bottom of the water column

BERM
- nearly horizontal part of beach or backshore formed of material deposited by wave action

BRACKISH
- water with a very low salt content (see oligohaline waters)

BIOACCUMULATION
- the accumulation of contaminants in the tissues of organisms through any route, including respiration, ingestion, or direct contact with contaminated water, sediment, or dredged material.

BIOPHYSICAL
- the biological and physical attributes of an ecosystem.

BIOTA
- the animal and plant life of a region

BIOTECHNICAL
- method of shoreline stabilization that utilizes natural materials to enhance slope stability and resist erosion This may include use of bundles of stems, root systems, or other living plant material, soft gabions, fabric or other soil stabilization techniques, and limited rock toe protection where appropriate. Biotechnical projects often include fisheries habitat enhancement measures in project design (e.g., anchored logs, root wads, etc.). Such techniques may be applied to creeks, rivers, lakes, reservoirs, and marine waters. Biotechnical may also be applied in upland areas away from the immediate shoreline.

BORROW PIT
- dredged area that supplies the sediment for a dike, levee, fill or a beach nourishment project.

BREACHING
- the breaking of a dike to allow re-entry of tidal flooding to tidal wetlands; can be caused naturally or artificially

BREAKER ZONE
- zone of shoreline where waves break

BUFFER
- a strip of land that is designed and designated to permanently remain vegetated in an undisturbed and natural condition to protect an adjacent aquatic or wetland site from upland impacts

CALANOID COPEPODS
- crustaceans in the Order Calanoida, of the Subclass Copepoda

CAPPING
- covering up of contaminated sediment with clean sediment in order to prevent toxic release into the environment.

CHANNEL
- a natural or artificial waterway of perceptible extent which either periodically or continuously contains moving water, or which forms a connecting link between two water bodies

CHLOROPHYLL
- green pigments essential to the process of photosynthesis, found primarily in plants; chlorophyll *a* is a specific type of chlorophyll pigment often used as an indicator of plant biomass

COASTAL ZONE
- includes coastal waters and the adjacent shorelands designated by a State as being included within its approved coastal zone management program. The coastal zone may include open waters, estuaries, bays, inlets, lagoons, marshes, swamps, mangroves, beaches, dunes, bluffs, and coastal uplands. Coastal-zone uses can include housing, recreation, wildlife habitat, resource extraction, fishing, aquaculture, transportation, energy generation, commercial development, and waste disposal

COMMUNITY
- association of plants and/or animals in a given area or region in which various species are more or less dependent upon each other

CONFINED DISPOSAL
- placement of dredged material within diked nearshore or upland confined disposal facilities (CDFs) that enclose the disposal area above any adjacent water surface, isolating the dredged material from adjacent waters during placement. Confined disposal does not refer to subaqueous capping or contained aquatic disposal.

CONFINED DISPOSAL FACILITY (CDF)
- an engineered structure for containment of dredged material consisting of dikes or other structures that enclose a disposal area above any adjacent water surface, isolating the dredged material from adjacent waters during placement. Other terms used for CDFs that appear in the literature include "confined disposal area," "confined disposal site," and "dredged material containment area."

CONTAINED AQUATIC DISPOSAL
- a form of capping which includes the added provision of some form of lateral containment (for example, placement of the contaminated and capping materials in bottom depressions or behind subaqueous berms) to minimize spread of the materials on the bottom.

CONTAMINANT
- a chemical or biological substance in a form that can be incorporated into, onto, or be ingested by and that harms aquatic organisms, consumers of aquatic organisms, or users of the aquatic environment.

CONTAMINATED DREDGED SEDIMENT OR MATERIAL

- those sediments or dredged materials that have been demonstrated to cause an unacceptable adverse effect on human health or the environment

COPEPOD
- crustacean in the subclass Copepoda; includes both pelagic (Calanoida, Cyclopoda) and benthi/epibenthic (Harpacaticoida)

CREST
- the seaward limit of a berm; Also, the highest part of a wave

CROSS-SHORE
- sediment traveling up or down the profile of a beach

CURRENT
- a flow of water

DEPOSITION
- the deposit of sediment in an area, can be by wave action, currents; or through mechanical means

DESICCATION
- critical loss of fluids; drying out

DELTA OR RIVER DELTA
- those lands formed as an aggregation feature by stratified clay, silt, sand and gravel deposited at the mouths of streams where they enter a quieter body of water. The upstream extent of a river delta is that limit where it no longer forms tributary channels

DEMERSAL
- pertaining to an organism, such as a fish, living close to or on the bottom of a body of water; describing the habitat close to or on the bottom

DENSITY
- the number of organisms per unit of area or volume

DIKE (see also LEVEE)
- a wall or mound built around low-lying area to control flooding

DISPOSAL SITE OR AREA
- a precise geographical area within which disposal of dredged material occurs

DREDGING
- the removal of earth, sand, gravel, silt, or debris from the bottom of a stream, river, lake, bay, or other water body and associated wetlands. Dredging is normally done for specific purposes or uses such as constructing and maintaining canals, navigation channels, turning basins, harbors and marinas, for installing submarine pipelines or cable crossings, or for dike or drainage system

repair and maintenance. Dredging may also be used to mine for aggregates such as sand and gravel.

DREDGED MATERIAL (previously called DREDGE SPOIL)
- the minerals and associated material removed by dredging, or material excavated from waters of the United States or ocean waters. The term dredged material refers to material which has been dredged from a water body, while the term sediment refers to material in a water body prior to the dredging process

DREDGED MATERIAL DISCHARGE
- any addition of dredged material into waters of the United States or ocean waters. This includes open- water discharges; discharges resulting from unconfined disposal operations (such as beach nourishment or other beneficial uses); discharges from confined disposal facilities that enter waters of the United States (such as effluent, surface runoff, or leachate); and overflow from dredge hoppers, scows, or other transport vessels

DREDGED MATERIAL DISPOSAL
- the depositing of dredged materials on land or into water bodies for either creating new or additional lands for other uses or disposing of the byproducts of dredging

DRIFT CELL, DRIFT SECTOR OR LITTORAL CELL
- a segment of shoreline along which littoral, or longshore, sediment movement occurs at noticeable rates. It allows for an uninterrupted movement, or drift, of beach materials

DRIFTWAY
- that portion of the shore process corridor, primarily the lower backshore and upper intertidal area, through which sand and gravel are transported by the littoral drift process.
Each drift sector includes: a feed source that supplied the sediment, a driftway along which the sediment can move, an accretion terminal where the drift material is deposited, and boundaries that delineate the end of the drift sector

DUNE
- a hill or ridge or sand piled up by the wind and/or wave action

ECOSYSTEM
- the organization of all biotic and abiotic factors in an area

ECOLOGICAL
- the interrelationship of living things to one another and to their environment

ECOLOGICAL FUNCTIONS
- those natural physical, chemical, and biological processes that contribute to the proper functioning and maintenance of aquatic and terrestrial ecosystems

EFFLUENT
- water that is discharged from a confined disposal facility during and as a result of the filling or placement of dredged material

EELGRASS (HABITAT)
- intertidal and shallow subtidal, unconsolidated sand to mud shores that are colonized by aquatic, submerged rooted vascular angiosperms (seagrasses) of the genus *Zostera*. Two species predominate in the Pacific Northwest: *Zostera marina*, the endemic eelgrass, and *Z. japonica*, an introduced cogener

EMERGENT MARSH
- intertidal shores of unconsolidated substrate which are colonized by erect, rooted herbaceous hydrophytes, excluding mosses and lichens

EMERGENCY
- regarding dredging operations, emergency is defined in 33 CFR Part 335.7 as a "*situation which would result in an unacceptable hazard to life or navigation, a significant loss of property, or an immediate and unforeseen significant economic hardship if corrective action is not taken within a time period of less than the normal time needed under standard procedures.*"

- the HPA rules define emergency as "*an immediate threat to life, public or private property, or an immediate threat of serious environmental degradation, arising from weather or stream flow conditions, other natural conditions or fire*"

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

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

ENTRAINMENT
when an organism is trapped in the uptake of sediments and water being removed by dredging machinery

EPIBENTHIC
- pertaining to the benthic boundary layer habitat at the interface between the bottom surface and the overlying water column, or to the organisms living in the habitat

EPIBENTHOS
- organisms that live on the surface of the bottom sediment. (see also epibenthic)

EPIPELAGIC
- pertaining to organisms which, through associated with the bottom, actively migrate off it into the water column, sometimes to the surface in shallow depths

EROSION
- the wearing away of land by natural forces; on a beach, the carrying away of the beach materials

ESTUARY
- the region near a river mouth where fresh water mixes with salt water and is influenced by the tide of marine waters

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

EUHALINE
- waters with a salinity range of 30-40 ppt

EUPHAUSIIDS
- crustaceans in the Order Eusphausiacea, of the subclass Malacostraca

EXTREME LOW TIDE
- the lowest line of the land reached by a receding tide.

FAUNA
- animal life (see also Flora)

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

FEEDER BLUFF OR EROSIONAL BLUFF
- any bluff or cliff experiencing periodic erosion from waves, sliding or slumping that, through natural transportation, contributes eroded earth, sand or gravel material via a driftway to an accretion shoreform. These natural sources of beach material are limited and vital for the long-term stability of driftways and accretion shoreforms (e.g., spits, bars, and hooks).

FEDERAL PROJECT
- any work or activity of any nature and for any purpose that is to be performed by or for the Secretary of the Army acting through the Chief of Engineers pursuant to Congressional authorizations. It does not include work requested by any other Federal agency on a cost reimbursable basis

FEDERAL STANDARD
- the dredged material disposal alternative or alternatives identified by the U.S. Army Corps of Engineers that represent the least costly alternatives consistent with sound engineering practices and meet the environmental standards established by the 404(b)(1) evaluation process or ocean-dumping criteria (33 CFR 335.7)

FISH AND WILDLIFE ASSEMBLAGES
- groups of species that are representative of all fish and wildlife species that commonly utilize specific estuarine habitats; not inclusive of all species, but each use, such as feeding, reproduction, etc. is represented; not guilds

FLORA
- plant life (also see Fauna)

FORESHORE
- part of the shore lying between the crest of a seaward berm and ordinary low water mark.

GRAVEL-COBBLE (HABITAT)
- intertidal shores which have substrates composed of a mixture of cobble and gravel where the habitat tends to be formed as beaches and bars, due to wave and current action, and seldom flats

HABITAT
- interacting physical and biological factors which provide at least minimal conditions for one organism to live or for a group of organisms to occur together. The specific area or environment in which a particular type of plant or animal lives. A habitat provides all of the basic requirements for the maintenance of life for an organism, a population or a community. Typical coastal habitats include beaches, marshes, rocky shores, bottom sediments, mudflats, and the water itself

HARPACTICOID COPEPODS
- crustaceans in the Order Harpacticoida, of the Subclass Copepoda

HYDRAULIC
- pertaining to water

HYDRAULIC PROJECT APPROVAL (HPA)
- permits issued by the Washington Department of Fish and Wildlife (WDFW) under chapter 77.55 RCW (formerly 75.20 RCW) to any person, organization, or government agency proposing to conduct activities which change, obstruct, divert or use the bed or flow of fresh and salt waters of the state. An HPA is either approved, conditioned, or denied based solely on protection of fish life under rules promulgated under chapter 220-110 WAC. Fish life includes all fish and shellfish at all stages of development.

HYDROPHYTES
- any macrophyte that grows in water or in a substrate that is at least periodically deficient in oxygen as a result of excessive water content; plants typically found in wetlands and other aquatic habitats

HYDROLOGY
- the dynamics of water movement through an area, as either surface (exposed) waters or subsurface (ground) waters

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

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

IMPOUNDMENT
- the retention or trapping of sediment in a location, either by natural or structural means

INFAUNA
- those organisms living within the sediments underlying a body of water

INFILTRATION
- water flow into the soil to replenish aquifers

INNER HARBOR LINE
- a line located and established in navigable tidal waters between the line of ordinary high tide and the outer harbor line and constituting the inner boundary of the harbor area

INTERSPECIFIC COMPETITION (see also Intraspecific competition)
- competition for resources between different species

INTERTIDAL
- the area exposed at low tides and inundated at high tides; defined as the area between Extreme Low Tide and Extreme High Tide

INTRASPECIFIC COMPETITION (see also Interspecific competition)
- competition for resources among individuals of the same species

INVERTEBRATES
- animals that lack a bony or cartilaginous skeletal structure.

INSOPEDS
- crustateans in the Order Isopoda, of the Subclass Malacostraca

LARVAE
- the immature form of an animal which is unlike the adult form and which requires fundamental changes before reaching the basic adult form

LITTORAL
- the benthic environment or depth zone between high water and low water, or pertaining to the organisms of that area

LEACHATE
- water or any other liquid that may contain dissolved (leached) soluble materials, such as organic salts and mineral salts, derived from a solid material. For example, rainwater that

percolates through a confined disposal facility and picks up dissolved contaminants is considered leachate

LEVEL BOTTOM CAPPING
- a form of capping in which the contaminated material is placed on the bottom in a mounded configuration

LIMNETIC
- waters in the salinity range of 0 – 0.5 ppt

LOCAL SPONSOR
- a public entity (e.g., port district) that sponsors Federal navigation projects. The sponsor seeks to acquire or hold permits and approvals for disposal of dredged material at a disposal site

MACROFAUNA
- animals with lengths between 0.5 mm and 5 cm

MANAGEMENT ACTION
- those actions or measures that may be considered necessary to control or reduce the potential physical or chemical effects of dredged material disposal.

MARINE
- waters associated with the ocean and that contain high salt content, as opposed to freshwater.

MARSH
- an area which is frequently or continually inundated with water, is generally characterized by herbaceous vegetation adapted to saturated soil conditions

MEAN HIGHER HIGH WATER (MHHW)
- height of the highest tidal waters, at a particular location, of each day averaged over a 19-yr period

MEAN LOW WATER (MLLW)
- height of the lowest tidal waters, at a particular location, of each day averaged over a 19-yr period

MEIOFAUNA
- animals (e.g., epibenthic, benthic) between 0.063 mm and 1.0 mm long

MESOHALINE
- waters with a salinity range of 3 –10 ppt

MICROBIOTA
- animals less than 0.063 mm long

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

MIGRATION
the seasonal travel of an animal between habitats.

MIGRATORY CORRIDOR
the physical pathway through which animals migrate.

MIGRATORY FISH
- those species utilizing nearshore habitats as they continue along their migratory corridor to the open-ocean to deeper pelagic waters. Their adult habitats are primarily not in nearshore areas. These include: chum, pink, chinook, coho, sockeye, coastal cutthroat, steelhead and bulltrout.

MITIGATION
- the process of avoiding, reducing, or compensating for the environmental impact(s) of a proposal, including the following:

A. Avoiding the impact altogether by not taking a certain action or parts of an action;
B. Minimizing impacts by limiting the degree or magnitude of the action and its implementation by using appropriate technology or by taking affirmative steps to avoid or reduce impacts;
C Rectifying the impact by repairing, rehabilitating, or restoring the affected environment;
D. Reducing or eliminating the impact over time by preservation and maintenance operations during the life of the action;
E. Compensating for the impact by replacing, enhancing, or providing substitute resources or environments; and
F. Monitoring the impact and the compensation projects and taking appropriate corrective measures.

MIXOHALINE
- waters with a salinity range of 0.5 – 30 ppt

MUDFLAT
- intertidal shores not vegetated by macrophytes, with unconsolidated sediment particles smaller than stones, predominately silt and is flooded at high tide and uncovered at low tide

NEARSHORE
-the beach, intertidal and subtidal areas along the shore of marine waters

NOURISHMENT
- process of replenishing a beach; naturally by longshore transport or artificially by deposition of dredged material. (beach nourishment)

NATURAL VARIABILITY

- error associated with estimates of populations which is attributed to their natural fluctuations, heterogeneous distribution or dispersal in the environment

NEARSHORE SUBTIDAL
- subtidal (depths > ELLW and ,20 m) zone adjacent to the shoreline or within an estuary

OFFSHORE
- the sloping subtidal area seaward from the low tideland

OLIGOHALINE
- waters in the salinity range of 0.5 – 3 ppt

OPEN-WATER DISPOSAL
- placement of dredged material in rivers, lakes, estuaries, or oceans via pipeline or surface release from hopper dredges or barges

OVERTOPPING
- passing of water over the top of a structure as a result of wave runup or surge action

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

PELAGIC
- pertaining to the water column or to an organism living within the water column

PHOTIC ZONE
- the surface waters of the ocean that receive light; where plants can photosynthesis

PHOTOSYNTHESIS
- the process by which plants utilize radiant energy from the sun to synthesize carbohydrates from carbon dioxide and water

PHYSICOCHEMICAL
- the physical and chemical properties of water.

PLANKTON
- suspended microorganisms that drift passively or have little power of locomotion in water and are subject to action of waves or currents.

POLYCHAETE
segmented worms of the phylum Annelida

POLYHALINE
-salinity level of 10-17 ppt

POINT

- a low profile beach promontory, generally of triangular shape whose apex extends seaward

PORTS
- centers for waterborne commerce and traffic.

PRIORITY HABITAT
- a habitat type with unique or significant value to one or more species. An area classified and mapped as priority habitat must have one or more of the following attributes:

A. Comparatively high fish and wildlife density;
B. Comparatively high fish and wildlife species diversity;
C. Important fish and wildlife breeding habitat;
D. Important fish and wildlife seasonal ranges;
E. Important fish and wildlife movement corridors;
F. Limited availability;
G. High vulnerability to habitat alteration; or
H. Unique or dependent species.

A priority habitat may be described by a unique vegetation type or by a dominant plant species that is of primary importance to fish and wildlife (such as, oak woodlands, eelgrass meadows). A priority habitat may also be described by a successional stage (e.g., old growth and mature forests). Alternatively, a priority habitat may consist of a specific habitat element (such as, consolidated marine/estuarine shorelines, talus slopes, caves, snags) of key value to fish and wildlife. A priority habitat may contain priority and/or non-priority fish and wildlife. [(§232-12-011 WAC)]

PRIORITY SPECIES
- fish and wildlife species requiring protective measures and/or management guidelines to ensure their perpetuation. Priority species are those that
meet any of the following criteria:

A. State-listed or state candidate species. State-listed species are those native fish and wildlife species legally designated as endangered (§232-12-014 WAC), threatened (§232-12-011 WAC), or sensitive (§232-12-011 WAC). State candidate species are those fish and wildlife species that will be reviewed by the department of fish and wildlife for possible listing as endangered, threatened, or sensitive according to the process and criteria defined in §232-12-297 WAC.
B. Vulnerable aggregations. Vulnerable aggregations include those species or groups of animals susceptible to significant population declines, within a specific area or state-wide, by virtue of their inclination to congregate. Examples include heron rookeries, seabird concentrations, marine mammal haulouts, shellfish beds, and fish spawning and rearing areas.
C. Species of recreational, commercial, and/or tribal importance. Native and non-native fish, shellfish, and wildlife species of recreational or commercial importance and recognized species used for tribal ceremonial and subsistence purposes that are vulnerable to habitat loss or degradation.
D. Species listed under the Endangered Species Act as either threatened or endangered. Federal candidate species are evaluated individually to determine their status in Washington and whether inclusion as a priority species is justified.

PRODUCTION
- the amount of organic matter generated per unit of time or area by a plant or an animal

PRODUCTIVITY
- the rate at which plants or animals generate organic matter

RECORD OF DECISION
- a comprehensive summary required by National Environmental Policy Act that discusses the factors leading to U.S. Army Corps of Engineers (USACE) decisions on regulatory and Civil Works matters and is signed by the USACE District Engineer after completion of appropriate environmental analysis and public involvement.

REGULATIONS
- in the context of the Marine Protection, Research, and Sanctuaries Act, means those regulations published in the Code of Federal Regulations, Title 40, Parts 220-227, and Title 33, Parts 209, 320-330, and 335-338 for evaluating proposals for dumping dredged material in the ocean. In the context of the Clean Water Act, refers to regulations published in the Code of Federal Regulations, Title 40, Parts 230, 231, and 233, and Title 33, Parts 209, 320-330, and 335-338 for evaluating proposals for the discharge of dredged material into waters falling under the jurisdiction of the Clean Water Act.

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

REFUGE
- habitat area that provides protection from predators or disturbance.

RELIEF
- the elevation features of a surface.

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

RENOURISHMENT
- the follow-up nourishment of a beach nourishment or fill project, often required in high-energy environments

RILL
- a very small drainage channel on a beach caused by seaward flow of water.

RIP CURRENT
- a strong surface current flowing seaward from the shore.

RESIDENT FISH – those fishes who remain in nearshore habitats throughout all of their life-history stages

RESTORATION
- the recovery of original ecological functions through measures such as native revegetation, removal of intrusive shoreline structures and removal or treatment of toxic materials.

RUNOFF
- the liquid fraction of dredged material or the surface flow caused by precipitation on upland or nearshore dredged material disposal sites.

SALINITY
- a measure of the concentration of dissolved salts in water, usually expressed as parts per thousand (ppt.) or as practical salinity units (psu)

SANDFLAT
- intertidal shores not vegetated by macrophytes, with unconsolidated sediment particles smaller than stones, primarily sand substrate and is flooded at high tide and uncovered at low tide.

SEASONAL RESIDENT-. fishes that move in and out of the eulittoral and shallow subtidal zones based on season and life-history strategies. nearshore zones. These include: Pacific herring, Pacific cod, walleye pollock, lingcod, and English sole.

SEDIMENT
- material, such as sand, silt, or clay, suspended in or settled on the bottom of a water body. Sediment input to a body of water comes from natural sources, such as erosion of soils and weathering of rock, or as the result of anthropogenic activities, such as forest or agricultural practices, or construction activities. The term dredged material refers to material which has been dredged from a water body, while the term sediment refers to material in a water body prior to the dredging process.

SEDIMENT DYNAMICS
- the physical processes that sediment particles are subject to in an area, such as longshore drift

SEEP
- location where groundwater rises above the land surface, or exits the soil on a slope

SHELLFISH
-aquatic and marine invertebrate animals possessing a hard outer covering, or shell. Shellfish include the mollusks, such as oysters and clams, and the crustaceans, such as shrimp and crabs

SUBTIDAL
- the area deeper than the line of Extreme Lower Low Water (ELLW)

SUSPENDED SOLIDS
- organic or inorganic particles that are suspended in water. The term includes sand, silt, and clay particles as well as other solids, such as biological material, suspended in the water column.

TERRITORIAL SEA
- the strip of water immediately adjacent to the coast of a nation measured from the baseline as determined in accordance with the Convention on the territorial sea and the contiguous zone (15 UST 1606; TIAS 5639), and extending a distance of 3 nmi from the baseline.

TOXICITY
- level of mortality or other end point demonstrated by a group of organisms that have been affected by the properties of a substance, such as contaminated water, sediment, or dredged material.

TOXIC POLLUTANT
- pollutants, or combinations of pollutants, including disease-causing agents, that after discharge and upon exposure, ingestion, inhalation, or assimilation into any organism, either directly from the environment or indirectly by ingestion through food chains, will, on the basis of information available to the Administrator of the U.S. Environmental Protection Agency, cause death, disease, behavioral abnormalities, cancer, genetic mutations, physiological malfunctions, or physical deformations in such organisms or their offspring.

TIDAL CHANNEL
- a channel through which water drains and fills intertidal areas

TRANSIENT FISH
- fishes that use nearshore eulittoral habitats on a temporally limited basis depending on their life-history phase. These fishes share a dependence upon nearshore intertidal and subtidal habitats for one or more of their life-history stages but use deeper habitats in other stages. These include: surf smelt, Pacific sand lance, and rockfish.

TURBIDITY
- a measure of the amount of material suspended in the water. Increasing turbidity levels of water decreases the amount of light that penetrates the water column. Abnormally high levels of turbidity can be harmful to aquatic life.

UPLANDS
- the area above and landward of a wetland or the intertidal shoreline

UPLAND ENVIRONMENT
- the geochemical environment in which dredged material may become unsaturated, dried out, and oxidized.

VESSEL
- a ship, boat, barge, or any other floating craft that is designed and used for navigation

WATERWAY
- a river, channel, canal, or other navigable body of water used for travel or transport

WETLANDS
- areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support and that, under normal circumstances, do support a prevalence of vegetation typically adapted for life in saturated-soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas (40 CFR Part 230).

WETLANDS RESTORATION
- returning a wetlands ecosystem to a close approximation of its condition prior to disturbance or other disruption of natural functions

YOUNG-OF-THE-YEAR
- animals at 0+ age, but less than 1 year in age

ZONING
- to designate, by ordinances, areas of land reserved and regulated for specific land uses.

ZOOPLANKTON
- the group of small, primarily microscopic, passively suspended or weakly swimming animals in the water column

APPENDIX C

Chemicals of Concern and Bibliography of Dredge Disposal and Contaminated Sediments Reports and Information Sources

Chemicals of Concern to Human Health from the Puget Sound Dredged Disposal Analysis (PSDDA) Program Dredged Material Evaluation and Disposal Procedures: A Users Manual for the Puget Sound PSDDA Program. February 2000. This document is online at: http://www.nws.usace.army.mil/dmmo/UMPDF.pdf

Table C-1. Chemicals of Concern

METALS
Arsenic
Antimony
Mercury (Methyl Mercury)
Nickel
Silver
ORGANIC COMPOUNDS
Flouranthene
Benzo(a)pyrene
1,2-Dichlorobenzene
1,3-Dichlorobenzene
1,4-Dichlorobenzene
Hexachlorobenzene
Dimethyl phthalate
Di-n-butyl phthalate
Bis(2-ethylhexyl) phthalate
Hexachloroethane
Hexaclorobutadiene
Phenol
Pentachlorophenol
Ethylbenzene
N-Nitrosodiphenylamine
Trichloroethene
Tetrachloroethene
Tributyltin
Total DDT + DDE
Chlordane
Dieldrin + Aldrin
Heptachlor + Heptachlor Epoxide
Total PCB's

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