7.4 Hydraulic and Geomorphic Modifications

Hydraulic and geomorphologic modifications associated with HPA projects occur in riverine, marine, and lacustrine environments. This section reviews what is known about the effects of these modifications on the movement of water (i.e., flow velocity, littoral currents) and the substrates in riverine, marine, and lacustrine environments, as well as the resultant impacts on HCP species. WDFW noted that miles of historical habitat have been permanently lost due to the placement of structures and fill, with commensurate permanent loss of riparian vegetation and large organic debris, as well as extensive intertidal habitat degradation from increased wave and current turbulence waterward of such structures (Canning and Shipman 1994).

7.4.1 Basic Hydrology, Hydraulic, and Geomorphic Influence on Habitat

Channel hydraulics refers to the flow of water in an open channel, such as a river, stream, or tidal channel, as well as the interactions between the flow and the channel boundaries. It also includes the concentrated flow of surface water across the land or the flow of water across a valley floodplain. It can also include the exchange of marine and fresh water in channels under tidal influence.

Water flowing in any open channel is subject to the external force of gravity that propels the water downslope as well as the friction between the water and channel boundaries that tends to resist the downslope movement (Leopold et al. 1964). Resistance to flow is caused by bed roughness, instream and bank vegetation, bank obstructions or irregularities, steps in the channel bed profile, and changes in channel alignment (Knighton 1998). All of these factors influence the hydraulic regime of a channel and dictate the channel morphology and the habitat characteristics of marine and freshwater ecosystems.

Activities that alter channel hydraulics can influence the channel morphology and in turn alter channel processes that create and sustain suitable habitats for fluvial and marine aquatic organisms. Conceptual models based on key relationships governing channel processes can be used to predict an array of possible channel responses to changes in sediment supply, transport capacity, and external influences such as changes in vegetation and woody debris loading (Abbe and Montgomery 2003; Brummer et al. 2006; Gilbert 1917; Lane 1955; Montgomery and Buffington 1998; Schumm 1971).

7.4.1.1 Freshwater Systems (rivers and streams)

Bolton and Shellberg (2001) provide a fundamental description of how water flows and activities in a channel affect flow.

> The amount of water passing a point on the stream channel during a given time is a function of velocity and cross-sectional area of the flowing water.

> $Q = AV$ (Equation 1)
> where Q is stream discharge (volume/time), A is cross-sectional area, and V is flow velocity. Equation 1 is a form of a mass-balance equation typically referred to by hydrologists as the Continuity Equation.
>
> If you confine the channel through various channelization activities, then the cross-sectional area decreases. If the channel must still carry the same flow or discharge (Q), then equation 1 shows that the flow velocity must increase. An increase in velocity results in an increase in the energy in the flow…(or) if you decrease the channel roughness or increase the channel slope, velocity increases. …an increase in velocity increases the energy of the flow and the amount of work that the water can do. This can lead to erosion of the channel bed and banks and transport of sediment downstream… Channel roughness is affected by substrate size, vegetation and large wood.

Miller et al. (2001) describe the basic concepts of geomorphic processes and their effect on riverine habitat.

> Streams are the arterial system of the land. The stream continuum begins with the smallest stream and ends at the ocean. Streams form a continuum of physical environments and associated aquatic and terrestrial plant and animal communities (Vannote et al. 1980). This continuum is a longitudinally connected part of the ecosystem in which downstream processes are linked to upstream processes.
>
> The characteristics of streams and streamflow in a particular watershed are defined by climatic parameters such as precipitation and temperature, as well as by physical factors such as topography, soils, geology, vegetation, and land use. The watershed provides two primary inputs that control channel form – water and sediment. These inputs ultimately drive fluvial processes and largely determine the nature of channel systems and channel process.
>
> Plants and animals have adapted to several distinct habitats that are characteristic of river corridors. These habitats can be subdivided into benthic, aquatic, and terrestrial zones (MacBroom 1998). The benthic zone consists of the streambed. Biota associated with the benthic zone are generally attached to or buried under the channel bed substrate. The aquatic zone is characterized by flowing water, and is associated with animals such as fish, (and) amphibians, and aquatic plants. Adjacent uplands make up the terrestrial zone, which is occupied by plants and animals that live on land that is rarely submerged for long periods of time.
>
> Fundamental fluvial processes include the downstream conveyance of water, sediment, nutrients, and organic matter. River geomorphology is also strongly affected by vegetation and geotechnical characteristics of channel boundary materials. The combination of factors associated with hydrology, climate, sediment transport, riparian vegetation, and boundary materials ultimately determines river channel form and process. The range of geomorphic processes

> that result include sediment entrainment, sediment deposition, floodplain inundation, recruitment of large woody debris, and creation and maintenance of riparian and aquatic habitat.
>
> Aquatic habitat is a product of fluvial processes, and diversity is a key component of productive stream habitat (Hill et al. 1991, Gore 1985, Poff et al. 1997). While geomorphologists may speak of channel forming flows in a relatively mechanical sense, biologists may view flow events in terms of their effects on aquatic habitat. Hydraulic forces differ both on a reach scale, locally (such as in the vicinity of a boulder or submerged log), and over the range of flows that a stream experiences. These forces create scour pools and transport, sort, and deposit coarse and fine bed materials, thus creating a diversity of bed forms and local substrate sizes (Lisle 1981). The resulting variety of depths, velocities, substrate types, and cover meets the needs of the various life stages of fish and other aquatic organisms (Gore 1985).

Additional useful sources of information on channel design include Bates (2003), Copeland et al. (2001), Papanicolaou and Maxwell (2000), and Watson et al. (1999).

7.4.1.2 Marine or Estuarine Systems

In marine environments, hydraulic and geomorphic processes also play important roles in creating and maintaining habitat for aquatic species. Shallow nearshore marine habitats, structured by tidal currents, wind, and input from terrestrial and freshwater sources, support spawning and larval settlement substrates as well as burrowing habitats for many of the HCP species (including juvenile salmon and rockfish species, cod, hake, Pacific herring, walleye pollock, Newcomb's littorine snail, and the Olympia oyster) (Bargmann 1998; Couch and Hassler 1990; Healey 1982; Larsen et al. 1995; Penttila 2001; Simenstad et al. 1979). The controlling factors in these habitats depend upon bathymetry, substrates, circulation and mixing, and sediment transport. These underlying hydrogeomorphic variables regulate a phenomenon known as longshore transport, or littoral drift (Komar 1998). Littoral drift is an important controlling factor in the determination of habitat structure; it is the transport and deposition of sediment that supports aquatic plants. Key to understanding littoral drift is the concept of a drift cell (also known as drift sectors), which is a segment of shoreline along which the longshore transport moves sediment at noticeable rates. Each drift cell includes: (1) a sediment source, such as a feeder bluff; (2) a driftway along which these sediments move; and (3) an accretion terminal where the drift material is deposited. In this way, a drift cell allows the uninterrupted movement of beach materials (Terich and Schwartz 1990; Cox et al. 1994).

Wave action striking shorelines at an angle causes littoral currents that move parallel to shore (Cox et al. 1994). While littoral processes are most conspicuous in marine waters, they can occur along lakeshores as well, where fetch and wind speed combine to produce waves and subsequent long shore currents strong enough to move shoreline sediments.

Shoreline features, including artificial structures, affect the velocity and direction of shoreline currents and sediment transport.

7.4.2 Mechanisms of Impact from Hydraulic and Geomorphic Modifications

HPA-permitted activities may result in altering the following processes:

- Riverine Environments
  - Altered Flow Conditions
  - Altered Channel Geometry
  - Altered Sediment Supply (Transport)
  - Altered Substrate Composition and Stability
  - Altered Groundwater/ Surface Water Interactions

- Marine Environments
  - Altered Wave Energy
  - Altered Current Velocities
  - Altered Nearshore Circulation
  - Altered Sediment Supply
  - Altered Substrate Composition

- Lacustrine Environments
  - Lakes
    - Altered Nearshore Circulation
      - Groundwater Input
      - Short-Period Waves
      - Buffering Capacity (WQ?)
  - Reservoirs
    - Altered Nearshore Circulation

Each of these mechanisms of impact may significantly affect the distribution, health, and survival of potentially covered species through direct or indirect adverse impacts on the habitat or other ecological life stage requirements of a given species. HPA-permitted activities that impose adverse impacts may in turn affect the population dynamics of fish and aquatic invertebrate species, either locally or on a broader regional scale. The magnitude of the potential impacts will depend upon:

1. The size, duration, and frequency of the impact.
2. The vulnerability of the affected life-history stage.
3. The ability of the organism to avoid the impact.
4. The physiological, developmental, and behavioral impairments suffered by the organism.
5. Indirect mechanisms such as exposure to predation.

7.4.2.1 Riverine Environments

River hydrology includes the movement of water in the stream, the movement of hyporheic groundwater to the stream, and the movement of surface water across land to the stream. It also includes the tidal delta hydrology and the river's exchange of marine and fresh water. Changes to riverine hydrology that reduce or increase the flow of water to the river alter the suitability of habitats within the river. During low-flow periods, alterations to hydrology can result in previously wetted areas going dry, thereby eliminating habitat area for aquatic organisms. Hydrologic alterations that increase overland surface water flow can, on the other hand, increase flooding and substrate scour.

Rivers are naturally dynamic systems that adjust to tectonic, climatic, and environmental changes (Dollar 2000). Environmental changes can be either human-induced or natural. The environmental components that contribute to channel processes are influenced by local and basin-scale variations in sediment supply, transport capacity, and the effects of vegetation (Montgomery and Buffington 1998). River systems adjust to maintain a steady state, or dynamic equilibrium, between the driving mechanisms of flow and sediment transport and the resisting forces of bed and bank stability and resistance to flow (Soar and Thorne 2001).

The quantity, quality, and diversity of aquatic habitats are the products of the fundamental channel processes entailing the conveyance of water, sediment, nutrients, and organic matter (Miller et al. 2001). The hydraulic forces acting in a river carve channels; recruit LWD; create scour pools; and transport, sort, and deposit coarse and fine bed materials. Riverine hydraulics determine the nature, as well as the distribution and deposition of, sediments and other materials along the path of the river's unidirectional movement toward lower elevations.

The resulting variety of depths, velocities, substrate types, and cover provides habitat diversity and meets the needs of the various life stages of fish and other aquatic organisms (Gore 1985). Fishes and invertebrates depend upon the diversity of habitats created by hydraulic forces (Montgomery et al. 1999). HCP species such as sturgeon, char, bull trout, salmonids, and freshwater mussels, depend on particular riverine sediment types, hydraulics, and habitats for reproduction, growth, and survival. Alterations to river hydraulics that change the flow of water and the ability of the water to move sediments and nutrients can have direct and indirect effects on HCP species. If flows become too strong, reaches of rivers can be made impassable to various fish species or life-history stages, or unsuitable for invertebrates. Projects that alter riverine hydrology can also have direct and indirect effects on HCP species.

Channels are defined by the transport of water and sediment confined between identifiable banks (Dietrich and Dunne 1993). Natural stream channels show great variety, reflecting differences in channel processes, disturbance regimes, structural controls, and geologic history (Washington Forest Practices Board 1995). One of the channel classification schemes most widely employed in Washington distinguishes channels primarily according to their roughness characteristics and their sediment transport regime (Montgomery and Buffington 1993, 1997). Some channel types addressed in this classification, i.e., **bedrock** and **colluvial channels**, are of little concern here because they seldom provide significant habitat for potentially covered species and because bedrock channels are unlikely to experience appreciable process change due to placement of artificial structures. **Alluvial channels** (as opposed to channels incised into bedrock) have erodible bed and banks comprised of sediments. An alluvial stream adjusts the dimensions of its channel to the wide range of flows that mobilize its boundary sediments. The adjustments of a river system are made over a continuum of spatial and temporal scales that result in corresponding gain, loss, or redistribution of habitat features.

In alluvial channels, a wide variety of channel types may develop. Montgomery and Buffington (1993) recognize six such channel types:

- cascade,
- step-pool,
- plane bed,
- pool-riffle,
- braided, and
- regime.

They propose that these types are controlled primarily by channel gradient and also by sediment supply (the amount of material available for transport) and transport capacity (determined by shear stress, which is similar to stream power). The singular importance of LWD as a structural element is also recognized. Changes in channel gradient, sediment supply, and stream power, which can be altered by placement of instream structures, therefore have the potential to directly alter habitat conditions for potentially covered species.

The steepest channels described by Montgomery and Buffington (1993) are **cascade channels**. Because of their high gradient (typically steeper than 8 percent), these channels usually have high roughness caused by boulder or bedrock bedforms. They typically have high transport capacity, so little sediment is stored in the bed or banks. The most common disturbance is debris flow. Cascade channels are predominant in small mountain tributaries in Washington, where they are often seasonal, non-fish-bearing streams. Some cascade channels, however, occur lower in the stream system, commonly where a stream transits a layer of relatively erosion-resistant rock; in such areas, they may link lower-gradient reaches having greater habitat value.

Step-pool channels commonly have a lower gradient of about 3 to 8 percent (Montgomery and Buffington 1993; Papanicolaou and Maxwell 2000). Many perennial, fish-bearing streams in hilly and mountainous parts of Washington have a step-pool morphology. Step-pool channels commonly provide spawning habitat for resident salmonids, especially when lower-gradient habitats downstream are utilized by anadromous salmonids (Montgomery and Buffington 1993). Step-pool channels are highly sensitive to the amount of LWD in a stream and to the stream's sediment supply; if LWD is removed from a step-pool channel, the channel's sediment storage capacity is reduced, sediment is transported from the reach, and the channel commonly shifts to a plane bed or pool-riffle morphology (Montgomery and Buffington 1993). This is an adverse habitat change for organisms that require deep and persistent pools, for example as cover or habitat buffer during low-flow periods. Severe increases in sediment supply also tend to cause loss of pools, again by filling, but step-pool channels tend to be robust against such a change, because filling pools reduces channel roughness, in turn increasing transport capacity and allowing scour to reestablish the pools (Montgomery and Buffington 1993). However, the pool filling and subsequent scour associated with this equilibration process could be expected to have adverse impacts on stream organisms. More moderate changes in sediment supply would also be expected to alter these channels, primarily by causing a general coarsening or fining of bed material. Generally, step-pool channels have a high enough gradient and transport capacity that it should be feasible to place additional roughness elements, such as artificial structures that occupy a fraction of the channel, without substantially altering channel hydraulics and sediment transport.

At more moderate gradients (typically 1 to 3 percent), the principal channel types are **pool-riffle** and **plane-bedded channels**. These channel types are highly vulnerable to hydraulic or sediment source changes, because they have low to moderate transport capacity; thus, relatively small changes in channel morphology can cause changes in net sediment accumulation or export, with associated changes in grain size and bedform (Montgomery and Buffington 1993, pg. 50). Normally, plane-bed channels have well-defined bed and banks with a lack of bedforms. LWD plays a critical role in pool-riffle and plane-bed channels. Adding LWD to a system will often cause a plane-bed channel to become a pool-riffle channel, while removing LWD will often cause the reverse transformation (Montgomery and Buffington 1993, pp. 41, 53). In channels that lack the transport capacity to move boulders, LWD provides the principal sites for both scour (which forms pools) and sediment accumulation (which forms riffles). Artificial instream structures such as abutments and pilings are often local sites for scour in these channels. In larger rivers with plane-bed channels, significant scour can occur, particularly in response to channel structures such as LWD (Sedell et al. 1986; Collins et al. 2002). This has been described, for instance, as the historical condition on the South Fork Nooksack River (Maudlin et al. 2002; Sedell and Luchessa 1982) and the Willamette River (Sedell and Froggatt 1984) and in the general case for larger Western Washington rivers (Abbé and Montgomery 1996).

Plane-bed and pool-riffle channels display a characteristic sensitivity to changes in sediment supply. Increases in fine sediment supply commonly lead to embedding, a process whereby fine sediments are incorporated to the bed of the stream and remain there after they become armored by a relatively thin surficial layer of coarse sediment. Embedding gives the stream a relatively hard, impervious bed that provides a poor substrate for salmonid spawning, impairs hyporheic exchange, and provides poor habitat for benthic invertebrate infauna. Typically, several years of peak flow events are required after the fine sediment inputs have ended for the bed to be sufficiently reworked that embedding abates.

Inputs of coarse sediment initially have little effect on pool-riffle channels, but as the inputs increase, the pools are filled, the channel aggrades, and the bedform changes from pool-riffle to plane bed (Montgomery and Buffington 1993). Continuing aggradation leads to channel widening and bar development (Montgomery and Buffington 1993). With sufficiently large increases in coarse sediment supply, the channel may develop a **braided** form (Montgomery and Buffington 1993).

Plane-bed and pool-riffle channels are among the most important for salmonid spawning because they have a bed mobility and scour regime to which salmon are well adapted, providing spawning habitat for large numbers of fish (Montgomery et al. 1999). These channels are also a principal habitat for freshwater molluscs, such as the potentially covered mussels, limpets, and spire snails.

The lowest-gradient channels, having gradients of less than 1 percent, are **regime channels** (Montgomery and Buffington 1993). These channels are abundant on floodplains and in tidewater areas of Washington. Regime channels are normally transport-limited and commonly have sand or silt beds. They are highly vulnerable to changes in sediment supply, alteration of bank vegetation, and artificial changes in gradient (Montgomery and Buffington 1993). Coarse sediment tends to fill the channel because the stream lacks the transport capacity to move it through the system. Finer sediment will be exported, but slowly; in the meantime, the channel tends to become wider and shallower (Montgomery and Buffington 1993). Because the bed and banks are comprised of relatively fine sediment, the roots of vegetation are particularly important to maintaining bank integrity; the loss of riparian vegetation can trigger bank erosion, causing sediment inputs and channel widening/shallowing (Montgomery and Buffington 1993, p 53).

All channels occur within a landscape context. Principal elements include the floodplain or channel migration zone, which is the area directly influenced by the channel during geologic time frames, and confinement, which is determined by the channel's proximity to neighboring hillslopes. Mountain channels (cascade and step-pool channel types) in Washington are often closely confined with no definable floodplain, but most fish-bearing channels do have a floodplain. Important structural and functional elements of floodplains and channel migration zones are described by Bolton and Shelberg (2001) and include:

- Channel complexity in the form of secondary channels, bars, channel sinuosity, and the way in which these change during floods
- Riparian ecosystems, particularly forested riparian systems that act as LWD sources and are subject to successional changes
- Groundwater and hyporheic components

Placement of structures within or beneath the stream channel can have the following primary effects on the channel (Brookes 1988, in Bolton and Shellberg 2001):

- channel shortened by straightening;

- channel cross-sectional area reduced (by placing fill, pilings, and/or abutments in the channel);
- channel bed and/or banks replaced with non-erodible artificial materials; and
- the channel loses the ability to migrate over time.

Channel roughness elements affect stream velocity by increasing boundary shear stress, thereby increasing resistance to flow (Leopold et al. 1964). Structures can increase or decrease channel roughness in a variety of ways that alter habitat, such as changes in in-channel roughness elements, changes in channel perimeter roughness elements, or changes in the relationship between channel area and wetted perimeter. All materials in contact with the wetted channel constitute roughness elements. The principal in-channel roughness elements are artificial structures such as gratings or pilings, and natural structures such as large woody debris.

An example of roughness effects on channels was encountered at a highway bridge reconstruction investigated by Barks and Funkhouser (2002), using a two-dimensional flow model to estimate conditions during the 100-year flood. Barks and Funkhouser (2002) found that relocating a bridge abutment from an area of dense vegetation to an agricultural area predicted a 67 percent decrease in channel roughness and a 29 percent increase in flow velocity, with associated high risk of scour and channel destabilization.

Because flow velocity is proportional to the product of roughness and wetted perimeter (Leopold et al. 1964), changes in the length of the wetted perimeter can also alter stream power. Structures in the channel alter the wetted perimeter directly, such as when flow is confined by a pier, or indirectly, such as when erosion or deposition causes changes in channel geometry. Structures such as docks and piers tend to confine the channel within artificial bounds and thus generally cause locally reduced channel roughness, potentially causing scour at the structure, with corresponding deposition downstream. Sturm (2004), modeling scour at bridge abutments in sandy sediments, found that scour could be significant enough to alter channel geometry, producing large excavations near bridge abutments and causing reduced water depths and sediment deposition immediately upstream. Sturm (2004) also found that this effect could be exacerbated in higher flows. The fact that the investigated abutment supported a bridge is immaterial; the structure represented by the abutment could have supported any kind of overwater structure, such a as pier. They used the same model to show that planting trees and placing riprap in the area would alleviate the predicted flow increase and move the area of maximum flow back into the stream's thalweg (the line of steepest descent along the stream). This study identified some of the principal channel border roughness elements, such as sediment, vegetation, and artificial elements like riprap and bridge abutments. This study underscores the importance of using hydraulic modeling to avoid locally significant changes in channel structure.

Each of these effects constitutes an "impact," but collectively these impacts affect channels primarily by altering only one controlling factor: stream power, which is in turn determined by water surface slope, flow volume, and channel roughness (Dunne and Leopold 1978). Structures placed in the channel have the potential to alter each of the factors identified in the above list. Because the surface of a stream is roughly parallel to its bed (Dunne and Leopold 1978), water surface slope is mainly altered by changes in channel gradient.

Channels are dynamic landscape elements that integrate inputs from tributary channels and from valley and hillslope processes (Washington Forest Practices Board 1995). Thus, a structure placed in a channel is likely, over time, to experience the effects of altered stream power and an altered sediment transport regime caused by changes in the watershed upstream. For example, in areas subject to progressive urbanization, gradual increases in catchment impervious surface cause predictable hydrologic changes characterized by increased variance in the hydrograph (Booth et al. 2002). One consequence of this change is increased peak flows and correspondingly increased sediment transport capacity, which often cause streambank instability and channel downcutting (Dunne and Leopold 1978, pp. 693-695). The resulting increases in flow and sediment around and through in-water structures can exceed the structures' design capacity, leading to outcomes such as scour around abutments and pilings, ponding upstream of culverts, culvert flow velocities that constitute a fish passage barrier, or a host of culvert structural problems.

To summarize, the placement of artificial structures in channels can, through a variety of mechanisms, cause increased erosion at or upstream of the structure, increased deposition downstream, and increased sediment transport past the structure. This amounts to a change in structural elements of the channel that relate to habitat such as channel type, substrate size distribution, channel cross-section, channel migration, bed mobility, and bank structure.

7.4.2.1.1 Altered Flow Conditions

The placement of pilings, fill, or nonerodible materials associated with the construction, operation, and repair of HPA projects can alter channel hydraulics through changes in roughness, channel geometry, and flow velocity. These changes are interrelated and can act in concert to modify channel morphology and interrupt natural habitat-forming processes (Montgomery and Buffington 1998) and even create predatory fish habitat (see Carrasquero [2001] for a related literature review). Increased velocities can indirectly affect various species by causing bed scour at channel obstructions (such as man-made structures) and corresponding sediment deposition downstream (Richardson and Davis 2001). Alterations to channel hydraulics that change the ability of water to transport and deposit sediment and nutrients can modify or eradicate suitable habitats for various lifestages of HCP species. Altered channel hydraulics can cause changes in nutrient flow, prey resources, and foraging opportunities which can result in reduced growth, fitness, reproductive success, and survival for both fish and invertebrates.

Pilings act as cylindrical flow obstructions that add hydraulic roughness to a channel. Likewise, fill placed in a channel can obstruct flow and add hydraulic roughness. Because flow velocity in a channel is proportional to hydraulic radius and inversely proportional to roughness (Leopold et al. 1964), adding pilings or hardening the bank can alter the flow velocity, depth, and width of a channel relative to natural conditions. The net effect of artificial fill or pile groups is to confine the flow. Riprap substrates (and, presumably, any substrates permanently simplifying channel margins) reduce complexity and diversity along the channel margin, leading to increased water velocity (Cramer et al. 2003). Hardened banks that replace riparian vegetation can increase the flow velocity and potential for scour and substrate coarsening through a reduction in hydraulic roughness compared to vegetated conditions (Millar and Quick 1998). Hard approaches to armoring tend to transfer energy downstream of the protected shore, and an increase in bank erosion and/or a loss of habitat in an adjacent reach can be readily anticipated (Cramer et al. 2003).

The primary effects of flow confinement by artificial structures are increased velocity and bed scour around structures and corresponding sediment deposition downstream (Richardson and Davies 2001). Scour is potentially an issue in all channel types, although it is most often a concern in alluvial plane-bed and pool-riffle channels, which have a relatively mobile bed. The term "scour" is usually used to refer to flow-driven horizontal excavation of the streambed, but it can also occur laterally along stream margins and result in bank erosion. Scour in stream and river systems chiefly occurs in conjunction with high-flow events that account for the largest fraction of annual sediment transport. Bed scour into a substrate of mixed particle sizes (i.e., sand and gravel) can selectively remove finer sediment and cause the substrate to coarsen. Likewise, deposition of the finer sediment downstream can bury organisms and cause the substrate to become finer.

The increased velocities and bedload movement associated with HPA-permitted modifications in the watershed that can impact peak flows encountered during flood events (e.g., bank protection, logging, addition of impervious surfaces, removal of riparian vegetation) exacerbate the natural scour conditions that fish may be adapted to and therefore can reduce egg survival. Substrate scour can affect fish egg nests by dislodging eggs and transporting them downstream before they have incubated sufficiently.

In addition to the location of the egg deposits in the channel and the bedload movement associated with flows, the vulnerability of these egg deposits depends upon the depth to which they are deposited. Montgomery et al. (1996) measured both scour and egg pocket burial depths of chum salmon and determined that a small increase in scour would affect the integrity of a large proportion of redds. There is a growing body of evidence (e.g., Montgomery et al. 1996, Montgomery et al. 1999) that salmon are adapted to natural bedload movement conditions. For example, based on observations that chum salmon bury their eggs just below scour depths during bankfull flow, Montgomery et al. (1996) hypothesized that the depths to which salmon bury their eggs represent an adaptation to the depths of scour during typical winter storms.

Further, Montgomery et al. (1999) provides evidence that salmon spawning distributions and timing are adapted to basin-specific scour conditions. These adaptations can result in salmon eggs being vulnerable to increases in the frequency and size of bedload movement associated with bank armoring. Such vulnerabilities could presumably be more severe for smaller fish species that bury eggs (e.g., lamprey, Olympic mudminnow, and resident trout). Smaller fish tend to spawn in smaller substrates and bury eggs at shallower depths than salmon and therefore may be more likely to be dislodged during unnaturally high scour events.

Freshwater mussels are particularly vulnerable to scour because they are long-lived, sessile organisms. Mussels are commonly found on relatively coarse (gravel to boulder) substrates in microsites that constitute flow refugia with low risk of scour (Cuffey 2002; Brim Box et al. 2004).

Increased scour can also have effects on floodplain processes. The geometry of a deepened channel disconnects it from the floodplain by creating a perched floodplain, or terrace, high enough above the channel that it is either no longer or less frequently inundated by the current hydrologic regime (Cramer et al. 2003). This can lead to abandonment of side channels and ponds in the short term and to reduction or prevention of sediment and nutrient delivery to the floodplain in the long term (Naiman and Bilby 1998). In addition, the formation of the terrace disconnects that surface from the water table and affects the establishment and survival of riparian vegetation. Other effects include bank instability as a result of oversteepening, groundwater discharge, increased shear stress because of very high peak flows within the channel, and loss of wetland/floodplain habitat and backwater areas.

Fish and invertebrates inhabiting riverine environments require certain flow velocities for spawning, rearing, migration, and foraging. Increases in flow velocities could present potential barriers to fish migration or could exceed thresholds for certain life-history stages of some HCP species.

- Chinook salmon tolerate velocities up to 49.9 ft/sec (15.2 m/sec) (Johnson et al. 2003) during migration.
- Pacific lamprey seek out slower velocities (0–0.33 ft/sec) for rearing (Stone and Barndt 2005).
- Optimal velocities for spawning habitat for mountain suckers in Lost Creek, Utah, are 2.4–7.9 in/sec (0.06–0.2 m/sec) (Wydoski and Wydoski 2002).
- Spawning velocities for Columbia River white sturgeon are similarly low (~2.6 ft/sec [0.8 m/sec]) (Paragamian et al. 2001), although this species spawns successfully in areas with higher average velocities by using river bed dunes and similar features for hydraulic refuge (Young and Scarnecchia 2005).
- Leopard and Umatilla dace inhabit riverine environments where the velocities are less than 1.6 ft/sec (Wydoski and Whitney 2003). Exceeding this velocity would render habitat unsuitable for these species.

Other species and life stages that may continue to use the habitat would need to expend higher energetic outputs to maintain position. This could impact growth rates and predation risks. In the case of larval fish, a study of fish use along natural and channelized habitats in the Willamette River, Oregon, concluded that continuous revetments are not good larval fish habitat (Li et al. 1984, in Bolton and Shellberg 2001). The authors determined that the combination of proximity to fast water, steep bank slopes, greater water depth, and cooler temperatures does not provide suitable habitat for larval fish.

Higher bank slope and velocity would also impact substrate composition and distribution such that the benthic and epibenthic invertebrates that are important in the diets of many fish species may no longer be as abundant or available. A shift in invertebrate species composition and abundance that affects diets would further exacerbate the problems created by increased energetic demand. As described by Bolton and Shellberg (2001), velocity is one of the critical factors contributing to the presence and abundance of macroinvertebrate species. Many species require low turbulence habitat for substrate. Bank protection activities that include channelization disrupt invertebrate communities (Bolton and Shellberg 2001). Reductions in the availability of prey can reduce the carrying capacity of a river system.

Direct and indirect effects of altered flow velocities on invertebrates are not well understood and represent an area for further research. However, for the HCP invertebrate species that are filter feeders (e.g., California floater and western ridged mussel) or rely on stable substrate for habitat structure, altered sediment transport is likely more important than changes in flow velocities.

Flow velocities influence swimming activity and respiration in fish species. Increased flow velocities during water releases can force fish species to rest in areas of slower moving water to recover from increased activity. This behavior can result in unsuccessful recruitment from delayed migration upstream for anadromous species (e.g., salmonids, sturgeon, lamprey), or increased predation from remaining longer in slow pools downstream of weirs and high-velocity reaches.

The addition of impervious surfaces is known to affect the hydrologic regime through changes in the magnitude, volume, and timing of flows (Booth 1991; Konrad 2000). Hydrologic changes that affect the velocity and depth of flows are considered a hydraulic alteration.

Increased impervious surface area can have local effects on water quality and flow conditions in streams and rivers, as well as on the cumulative effects of urbanization within a watershed. In particular, reduced infiltration can alter stream hydrology such that peak flow levels are increased and base flow levels decreased. Changes in peak flow volumes and the rates at which peak flow levels rise and fall can lead to damaging changes in channel morphology and substrate composition. Decreased base flow levels in summer months can reduce the amount of suitable habitat area available for aquatic species, as well as lead to unfavorable changes in the water temperature regime. Stormwater runoff from impervious surfaces is also likely to carry a range of pollutants known to have detrimental effects on aquatic species, including PAHs, metals, and organic compounds including pesticides, herbicides, fertilizers, and other substances.

7.4.2.1.2 Altered Channel Geometry

The alteration of channel processes and morphology can impact fish and invertebrates through the reduction of habitat quantity, quality, and diversity. These impacts can range from subtle shifts in the distribution and abundance of species to complete dislocation of a species from a particular locale. The reproduction, growth, and survival of HCP species depend upon particular channel hydraulics to maintain their specific habitats. Alterations to channel geometry can result in reduced growth, fitness, reproductive success, and survival.

The range and magnitude of potential responses of the channel to hydraulic and geomorphic changes and how these responses are transmitted downstream in riverine environments depend on the channel type and location of the disturbed reach in the drainage basin (Montgomery and Buffington 1997; Schumm 1971). The availability of backwater areas and off-channel habitat can be reduced by bank protection structures. Habitat quantity and complexity will be reduced by the shortening of the river and narrowing of the river cross section. The reduction in the amount of side channel and floodplain areas can impact fish species that rely on any of the associated habitats, including wetlands, beaver ponds, bogs, and off-channels.

Vannote et al. (1980) proposed the river continuum concept to describe freshwater habitat and the importance of various physical, chemical, and biological processes. According to the river continuum concept, the distribution of stream characteristics reflects a headwater to mouth gradient of physical conditions that affect the biological components in a river including the location, type, and abundance of food resources with a given stream size. The ecological significance of a potential channel response to channel modification depends on the species of interest.

Alteration of channel geometry has both direct and indirect effects on fish and invertebrates. Indirect impacts arising from the alteration of channel geometry include the modification of natural sediment transport, a reduction in habitat connectivity, and a reduction in habitat complexity. Fish and invertebrates require certain widths and depths for habitat, spawning, and cover.

As a result of the loss of side channel and floodplain habitats during high-flow events, fish could be displaced downstream or would require higher energetic outputs to maintain position in the higher velocities. For territorial species or life stages (e.g., coho juveniles), the displacement would require the fish to locate and establish a new territory with suitable habitat conditions. Presumably, this could impact any fish that may have been occupying the new habitat and trigger its displacement.

- The loss of side channel and floodplain habitats reduces the availability of refuge habitat during high flows as well as summer rearing and overwintering habitats for juvenile salmonids and other small fish species.
- Juvenile coho salmon are particularly impacted by a reduction in off-channel habitats and beaver ponds, and numerous studies have documented their reliance

on those habitat types (e.g., Brown and Hartman 1988; Bustard and Narver 1975; Swales and Levings 1989). In Carnation Creek watershed (a drainage in Vancouver, British Columbia), between 15 and 25 percent of the total coho smolt yield was captured in off-channel sites (Brown and Hartman 1988, in Henning 2004).

- Chinook (Swales and Levings 1989), sockeye (Burgner 1991), chum (Salo 1991), and steelhead (Puget Sound Steelhead Biological Review Team 2005) all rely on off-channel habitats to a lesser extent, but would be impacted by the loss of habitat.
- Pink salmon rely very little on off-channel habitats (Heard 1991) and would therefore be least impacted by the reduction of such habitats.
- Among trout and char, coastal cutthroat utilize off-channel environments the most (Lister and Finnigan 1997) and would be the most likely to be impacted by the loss of habitat.
- The loss of side channel and floodplain habitat could also impact species such as lamprey and mountain suckers that rely on slow-moving backwater areas for habitat.
- Olympic mudminnows require access to floodplain wetlands and bogs. In an investigation of the role of regulated floodplain wetlands in the Chehalis River as rearing (i.e., feeding and refugia) habitat for fishes, Henning (2004) documented high fish utilization in seasonally flooded habitats. The study captured 19 different fish species, including juvenile salmonids, Olympic mudminnows, and Pacific lampreys. Based on the high number and frequency of catch, it appears that these seasonally flooded habitats are preferred habitats for Olympic mudminnows (Henning 2004).

7.4.2.1.3 Altered Sediment Supply

Channel morphology (i.e., width, depth, bed slope, substrate size, bed forms, and pattern) is influenced by both local and downstream variation in sediment input from watershed sources (sediment supply), the ability of the channel to transmit these loads to downstream reaches (transport capacity), and the effects of instream woody debris and bank vegetation on channel processes (Montgomery and Buffington 1998). The relationship between these controlling factors is illustrated in Figure 7-2.

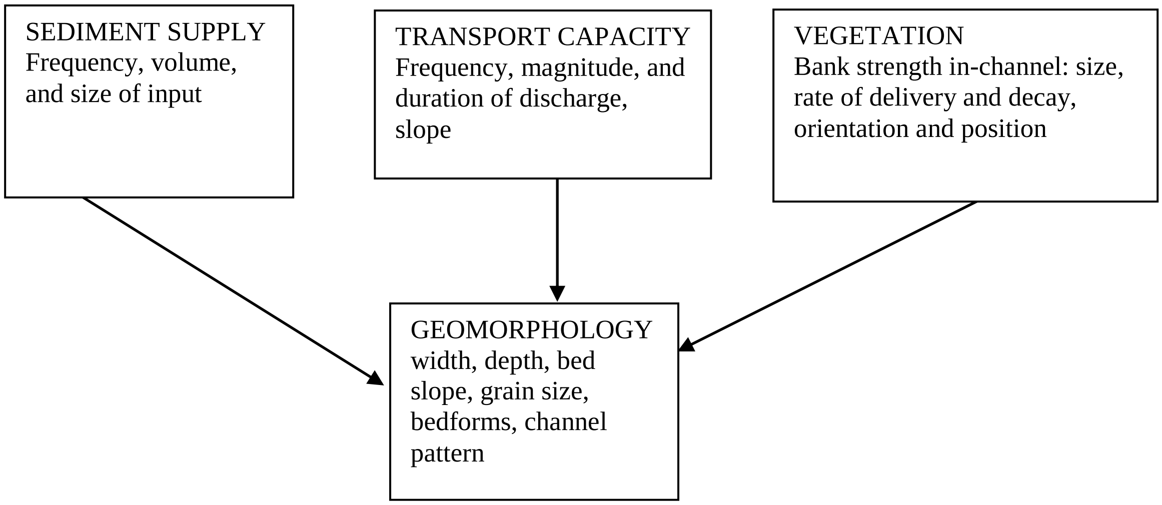

Figure 7-2. Riverine hydraulic controlling factors (adapted from Montgomery and Buffington 1998).

Because the rate and caliber of sediment supplied to a channel influences the substrate size (Dietrich et al. 1989), changes in sediment supply can alter the composition of substrate used by HCP species. Modifications affecting sediment supply may include increased scour of substrate and increased deposition of substrate. Scour and deposition may include impacts that can extend far beyond the project site.

Because HCP species depend on the presence or absence of particular substrate types to support important life-history functions, changes in sediment source contributions can have direct and indirect effects on those species. Fish and invertebrates require a range of substrate conditions in riverine environments for various life-history stages. These conditions rely on the replenishment of suitably sized substrates to offset natural sediment transport processes that remove sediment. In a study in California, the primary cause for the decline of salmon in the Sacramento River was linked to the loss of spawning gravels normally derived from bank erosion before riprap bank stabilization (Buer et al. 1984).

On the other hand, excessive sediment supply can affect fish and invertebrate species. Deposition effects depend on the particle size distribution and amount of sediment. For example, when sedimentation occurs, salmonids may be negatively affected in several ways: buried salmonid eggs may be smothered and suffocated; prey habitat may be displaced; future spawning habitat may be displaced (Spence et al. 1996; Wood and Armitage 1997), and juveniles and small fish may be prevented from using the interstices as refuge (Spence et al. 1996).

Channel incision, floodplain disconnectivity, and reduced lateral migration all contribute to a reduction in the recruitment of LWD, organic matter, and gravel. LWD is a major component of pool formation, channel braiding, cover, and habitat complexity (Bisson et al. 1987). Woodsmith and Buffington (1996) found that the number of pools in a channel system was highly correlated with the quantity of LWD. In contrast to areas where bank protection disconnects the river from the floodplain, inundation of floodplain areas recruits additional organic matter and nutrients that provide the base of a productive food web, which can result in high yields of fish (Bayley 1991, 1995). Gravel sources along river routes supply substrate for the continual natural replacement and transport downstream. In-channel gravel provides several functions for multiple trophic levels, including spawning substrate for fish, attachment points for sedentary invertebrates and aquatic vegetation, and habitat for epibenthic invertebrates.

7.4.2.1.4 Altered Substrate Composition and Stability

Alteration of the substrate composition through coarsening or fining of the bed can have direct and indirect effects on HCP species. The ecological effects of substrate coarsening and fining on salmonids and trout in riverine environments are well known.

Bed scour into a substrate of mixed particle sizes (i.e., sand and gravel) can selectively remove finer sediment and cause the substrate to coarsen. Likewise, deposition of the finer sediment downstream can bury organisms and cause the substrate to become finer. For blunt objects, the depth and extent of bed scour depend on the water depth, approach velocity, and shape and size of the obstruction (Richardson and Davis 2001). Increased bed scour and substrate coarsening are detrimental to habitat suitability. Scour and substrate coarsening are often accompanied by an increase in the interlocking strength of bed particles and the threshold force necessary for bed mobility, leading to bed armoring (Church et al. 1998; Konrad 2000; Lane 1955).

At the outset of spawning, adult fish winnow fine sediment from their gravel redds, mobilizing fine sediment into the water column and in the process coarsening the bed in the immediate vicinity of the spawning nest (Kondolf et al. 1993; Montgomery et al. 1999). However, if fine sediments are deposited again after redd construction, this material fills pore spaces between gravel particles in and over the redd.

Deposition of fine sediment may degrade instream spawning habitat and reduce survival from egg to emergence by smothering interstices (Chapman 1988; Phillips et al. 1975; Zimmermann and Lapointe 2005). Excessive deposition of fines can lead to substrate embeddedness, reduce the water circulation necessary to oxygenate the eggs, and reduce flushing of metabolic waste (Bjornn and Reiser 1991; Zimmermann and Lapointe 2005). Embryo mortality has been found to occur from poor water circulation and lack of oxygenation associated with the filling of intergravel pore spaces by fine sediment (Bennett et al. 2003 Chapman 1988; Cooper 1965; Lisle and Lewis 1992). The probability of pore space filling increases if the sediments are particularly fine, if the sediment amount is large, and if flows/currents are relatively low (Bjornn and Reiser 1991). For salmon, the process may be exacerbated by downwelling hyporheic flows, which often occur at salmonid spawning sites in Pacific Northwest rivers (Tonina and Buffington 2003, 2005). In a study of spawning chum salmon in low-gradient, gravel-bed channels of Washington and Alaska, Montgomery et al. (1996) found that minor increases in the depth of scour caused by bed fining and reduction in hydraulic roughness significantly reduced embryo survival. Dolly Varden prefer gravel as a spawning substrate (Kitano and Shimazaki 1995).

The amount of sediment does not need to be large to cause smothering effects. Although redds of large salmonids are usually buried beneath at least 6 inches (15 cm) and as much as 1 foot (30 cm) of gravel (Bjornn and Reiser 1991; DeVries 1997), near-surface deposits of fine sediment may be sufficient to reduce water flow through the redd and create a surface layer that physically prevents alevin emergence (Bjornn and Reiser 1991; Everest et al. 1987). Fines under approximately 0.03 inch (0.85 mm) in diameter have been shown to be particularly detrimental to salmon eggs through the associated decrease in dissolved oxygen (Chapman 1988). Research has documented significant declines in salmonid egg survival when the percentage of fine sediments under 0.03 inch (0.85 mm) in diameter reaches the range of 10 percent (Tappel and Bjornn 1983) to 13 percent (McHenry et al. 1984; see Chapman 1988).

Salmon require a range of sediment sizes, and spawning success depends on how well they can mobilize sediment with their tail to create a redd. Different species of salmon use gravels of different size and can effectively move only certain size classes of sediment (Kondolf 1997; Kondolf and Wolman 1993). During redd building, salmon avoid substrates larger than those they can mobilize (Kondolf and Wolman 1993; Kondolf al. 1993). This includes areas where erosion to bedrock has occurred. Field observations have shown that salmonids can build redds where the average substrate size (D_{50}) is up to 10 percent of average body length (Kondolf and Wolman 1993). Recommended average sizes for spawning gravels are listed in Table HG-1.

Table 7-5. Spawning gravel criteria for salmonids.

Gravel Bed Criteria	Small-Bodied Salmonids (<13.8 in) (<35 cm)	Large-Bodied Salmonids (>13.8 in) (>35 cm)
Dominant substrate particle size	0.3–2.5 in (8–64 mm)	0.6–5 in (16–128 mm)
Minimum gravel patch size	10.7 ft2 (1.0 m2)	21.5 ft2 (2.0 m2)

Note: Small-bodied salmonids include cutthroat trout. Large-bodied salmonids include coho and Chinook salmon and steelhead trout (after Schuett-Hames et al. 1996).

Embedding also reduces prey for foraging juvenile salmon by promoting a shift from epibenthic to benthic infaunal macroinvertebrates, which are not easily preyed upon by young salmonids (Bash et al. 2001; Suttle et al. 2004).

Although far less is known about the effects of changes in substrate on the life-history stages of other freshwater fish and invertebrates than on salmonids, a few studies have been done.

- White sturgeon prefer gravel and cobble substrate for spawning because their adhesive eggs are susceptible to burial by sand and silt-sized substrate (Paragamian et al. 2001).

- Mountain suckers in Lost Creek, Utah, showed a preference for spawning depths of 4.3–11.8 inches (11–30 cm) (Wydoski and Wydoski 2002).

- The deposition of fine sediment can adversely impact invertebrates (Wantzen 2006). Fine sediment particles may clog biological retention mechanisms such as the filtering nets of caddisfly larvae, or the filtering organs of mollusks.

- Overburden from increased deposition has been shown to adversely affect invertebrates having low motility (Hinchey et al. 2006).

- Sediment deposition can impair the growth and survival of filter-feeding organisms or organisms living on the substrate (Bash et al. 2001) by filling interstitial spaces needed for respiration and feeding.

- In freshwater mussels, Tucker and Theiling (1998) described a study in which fine sediment (silt) deposition of as little as 0.25 inch (6.35 mm) caused death in mussels. Siltation also is detrimental to young mussels and reduces their survival (Scruggs 1960, in Tucker and Theiling 1998). Juvenile survival (even of hardy species) may be reduced in silt-impacted mussel beds, which can limit recruitment of young in the entire bed (Tucker and Theiling 1998). While the exact mechanisms are not known, it is clear that siltation causes changes in water flow through the gravel and results in a shift in algal and microbial communities (Tucker and Theiling 1998).

- Different mussel species show varying responses to fine sediment inputs (Brim Box and Mossa 1999). Freshwater mussels are nearly sedentary filter feeders and occupy stable gravel substrate; therefore, they are sensitive to changes in channel hydraulics and sediment transport. Erosion of suitable substrate could dislodge the animals (Brim Box et al. 2004). McDowell (2001, in Brim Box et al. 2004) found that populations of western pearlshell (Margaritifera falcata), a freshwater mussel, were denser in reaches of the Middle Fork John Day River having no channel modification compared to modified reaches.

7.4.2.1.5 Altered Ground Water/Surface Water Interactions

The exchange of groundwater and stream flow through the hyporheic zone can provide several important ecological functions, including retention and storage of water, regulation of water releases to streams, promotion of habitat complexity, regulation of stream temperatures, refuge for fish eggs and invertebrates, and nutrient enrichment (Bolton and Shellberg 2001).

Hydraulic and geomorphic modifications can result in altered groundwater/surface water exchange through several pathways. Changes in channel form can affect the interaction between groundwater and surface water. Principally, channel aggradation or downcutting leads to altered surface water elevations, which affects the groundwater/surface elevation and groundwater flux to the channel. Bank erosion and substrate alterations can also alter these dynamics.

HPA-permitted structures that alter groundwater dynamics in riverine systems can directly affect fish and invertebrates in the short-term by influencing water quality and habitat suitability or availability. In the long-term, changes to groundwater exchange can generate indirect effects on fish and invertebrate species by affecting low flow conditions (i.e., increasing the magnitude of periods of drought resulting in reduced habitat availability and suitability, potential stranding or desiccation), and by affecting water quality through warmer stream temperatures and decreased organic and nutrient inputs.

The interplay between groundwater and surface water in the hyporheic zone has become increasingly recognized as a key process in the ecological functioning of riverine ecosystems. Changes in flow regime, sediment transport, and substrate composition all affect in-channel hyporheic exchange. In riverine environments, connectivity is generally expressed in three dimensions: longitudinally (upstream–downstream), laterally (channel–floodplain), and vertically (channel–hyporheic zone [the interface between surface and groundwater]) (Edwards 1998; Stanford and Ward 1992). The quality of habitat connectivity in one dimension may affect that in another dimension. For instance, the hyporheic zone serves as a medium across which dissolved organic matter and nutrients are exchanged between the riparian zone and surface water. A high level of substrate fines within the channel substrate may hinder the connection between surface and groundwater, limiting vertical and lateral connectivity (Edwards 1998; Pusch et al. 1998).

The presence of large woody debris in channels has been linked to increased hyporheic exchange (Mutz and Rohde 2003). The addition of LWD to channels has been shown in most cases to increase channel complexity. Log jams can cause stream flow to separate, (Abbe and Montgomery 1996), and part of the flow may be directed into the bed and banks of the channel. While a study by Sweka and Hartman (2006) found that large woody debris additions to eight Appalachian streams did not increase pool area, a number of other studies have shown that LWD presence increases pool frequency (Baillie and Davies 2002; Beechie and Sibley 1997) and area (Brooks et al. 2004; Cederholm et al. 1997; Hilderbrand et al. 1997). Increased pool density will be accompanied by an increase in pool-riffle transition zones. These areas are “hot-spots” of hyporheic exchange because head differential through the transition zone forces surface waters through the stream bed (Tonina and Buffington 2007). Consequently, through pool creation, LWD additions can increase hyporheic exchange rates. Conversely, the removal of LWD will decrease pool density (Ensign and Doyle 2005), act as a catalyst for incision (Diez et al. 2000), and thus reduce hyporheic exchange throughout the channel.

Lack of connectivity can degrade conditions for riparian zone vegetation, reducing LWD recruitment to the stream channel and subsequently limiting habitat-forming and maintaining processes and habitat complexity. Ecological connectivity is essential between riverine and riparian ecosystems (Kelsey and West 1998; Stanford and Ward

1992). Effects on ecological functions and freshwater aquatic species associated with degraded groundwater/surface water connectivity are well documented (Bilby and Bisson 1998; Hershey and Lamberti 1992; Karr 1991; Kelsey and West 1998; Montgomery et al. 1999; Naiman et al. 1992; Reiman and McIntyre 1993; Stanford and Ward 1992; Stanford et al. 1996).

Stream temperature is an important factor in determining the suitability of habitats for aquatic species. The interface between flow within the hyporheic zone and the stream channel is an important buffer for stream temperatures (Poole and Berman 2001a), so alteration of groundwater flow can affect stream temperature. The magnitude of the influence depends on many factors, such as stream channel flow patterns and depth of the aquifer (Poole and Berman 2001a).

The preferential selection of spawning substrates in groundwater upwelling zones is a common behavior among all HCP salmonid species (Baxter and Hauer 2000; Berman and Quinn 1991; Bjornn and Reiser 1991; Ebersole et al. 2003; Geist 2000; Geist and Dauble 1998; Geist et al. 2002; Greig et al. 2007; Zimmermann and Lapointe 2005). The disruption of flow through the hyporheic zone can affect fish spawning.

- In Montana, the distribution and abundance of bull trout is influenced by hyporheic and groundwater–surface water exchange (Baxter and Hauer 2000).
- Female bull trout tend to choose areas of groundwater discharge (i.e., cooler temperatures) for locating their spawning, and upwelling sites serve as important thermal refugia for all life-history stages (Baxter and McPhail 1999).
- Geist (2000a, 2000b) found that fall Chinook salmon chose spawning sites in the Hanford Reach of the Columbia River where groundwater was upwelling; where there was no upwelling, no spawning activity occurred. The dissolved oxygen content of upwelling groundwater was 9 mg/L, but only 7 mg/L or less where there was no hyporheic discharge (Geist 2000a, 2000b).

HPA-permitted activities that adversely affect groundwater upwelling may limit the availability and suitability of spawning and thermal refuge habitats.

Increased vertical exchange between surface and subsurface waters benefit aquatic biota by increasing benthic dissolved oxygen levels and promoting solute uptake, filtration, and transformation. Studies have shown that the availability of dissolved oxygen to incubating salmonid embryos is dependent upon hyporheic exchange (Geist 2000; Greig et al. 2007) and that the occlusion of this exchange through siltation can lead to hypoxia within redds and decreased embryo survival (Heywood and Walling 2007). The hyporheic zone does more than promote oxygen exchange in subsurface sediments, it can also act as an effective filter and zone of biogeochemical transformations.

Hyporheic exchange has been shown to influence water quality and food web productivity in flowing water ecosystems at multiple levels (Anbutsu et al. 2006; Ensign and Doyle 2005; Fernald et al. 2006; Jones et al. 1995; Lefebvre et al. 2005; Mulholland et al. 1997; Sheibley, Duff et al. 2003; Sheibley, Jackman et al. 2003; Tonina and Buffington 2003; Tonina and Buffington 2007; Triska et al. 1989; Valett et al. 2005). Increased hyporheic exchange has been associated with nutrient uptake (Anbutsu et al.

2006; Sheibley et al. 2003) and transformation (Fernald et al. 2006; Lefebvre et al. 2005), and may attenuate the transport of dissolved and particulate metals (Gandy et al. 2007). Elevated metals and nutrients can both have negative ramifications for fish and invertebrate health.

Any activity which impacts the functioning of the hyporheic zone, such as the removal of LWD, could impose an array of stressors on HCP species occurring in the affected environment through a number of related impact mechanisms. Hydraulic and geomorphic modifications that alter hyporheic zone functions are likely to impose some level of indirect effects on aquatic habitat conditions. By extension, this suggests the potential for adverse effects on HCP species dependent on these environments.

7.4.2.2 Marine Environments

7.4.2.2.1 Altered Wave Energy

The redistribution of wave energy can have a number of interrelated indirect and direct impacts on fish and invertebrates. Alterations to wave energy can cause changes in substrate and alter water column characteristics. Waves produce motions and induce transport both in the water column and near the seabed that are capable of transporting particulates large distances (Liang et al. 2007; McCool and Parsons 2004). Altering these mechanical processes alters transport rates (Liang et al. 2007; McCool and Parsons 2004). Wave action creates complex littoral habitat by removing fine or silty sediments (Beauchamp et al. 1994). Wave action may also be a source of desirable spawning substrate.

Wave energy is the dominant source of fluid mechanics in the nearshore area in most of Washington waters (Finlayson 2006), responsible for mixing the upper portion of the water column (Babanin 2006) and producing high shear stresses near the bed (Lamb et al. 2004). Shear stress is the force applied to the bed and also related to the intensity of the turbulence in the water column. Reduction in wave energy from natural levels lowers the near bed shear stress, resulting in the deposition of finer sediments (Miller et al. 1977). Considering the large volume of fine-grained sediment supplied to western Washington waters (Downing 1983), even areas that are not part of an active littoral cell can receive a large amount of fine sediment.

Attenuation of waves can increase water column stratification in marine waters and lead to dissolved oxygen reduction and temperature anomalies (Qiao et al. 2006). Surficial mixing and circulation also play an important role in primary productivity, particularly near large river mouths (e.g., Willapa Bay [Roegner et al. 2002]). Disruption of mixing and circulation may adversely affect primary productivity and marine species through the disruption of food web dynamics.

Changes in wave energy across substrates determine the size and distribution of sediments and associated detritus (Nightingale and Simenstad 2001b). Throughout Puget Sound, Hood Canal, and Washington’s coastal estuaries, variations in the interface between bottom slopes, wave energy, and sediments build beaches, nearshore substrates, and habitats unique to the climate, currents, and conditions of specific sites (Nightingale and Simenstad 2001b). Although specific characteristics of the factors at play vary with the geology of each region or subsystem, changing the type and distribution of sediment will generally alter key plant and animal assemblages (Nightingale and Simenstad 2001b).

Alterations in the natural distribution of wave energy can prove harmful to aquatic vegetation as well as the fish and invertebrates that use and consume them (Eriksson et al. 2004; Sandstrom et al. 2005). Wave energy plays a role in the distribution of aquatic vegetation used by salmonids and other nearshore fishes, particularly in energetic environments. High wave energies have been shown to inhibit the colonization and growth of some seagrasses (e.g., eelgrass) (Fonseca and Bell 1998); although in more recent studies in Puget Sound, no correlation was found between eelgrass prevalence and wave characteristics (Finlayson 2006). High wave energy can also dislodge kelp (Kawamata 2001).

The only direct impact of extreme wave energy would be on those invertebrates that cannot tolerate extremely high shear stresses or burial. If the shear stress exceeds the force securing invertebrates to the seabed, they become entrained into the water column and destroyed. Intense turbulence may also disrupt migration of fish. Experimental evidence of the mortality limits of large shear stresses on mollusks or other invertebrates is not available.

Increased wave energy may suspend and redistribute sediments, which may result in burial of invertebrates. Olympia oysters, the only marine HCP invertebrate species prone to this sort of burial, have been shown to be intolerant of siltation and do best in the absence of fine-grained materials (WDNR 2006b). The partial and complete burial of closely related estuarine mollusks has been addressed empirically (Hinchey et al. 2006). Results of these studies indicate that species-specific responses vary as a function of motility, living position, and inferred physiological tolerance of anoxic conditions. Mechanical and physiological adaptations contribute to this tolerance. Motile organisms are much more capable of surviving high sedimentation rates than sedentary ones such as the Olympia oyster. Survival of each species examined appeared to decrease exponentially with increasing overburden stress (i.e., depth of burial), with most species being killed once they were completely buried. Most shorelines in Washington do not experience the sedimentation rates that result in burial-related mortality. However, near river mouths, alterations in sedimentation rates are possible that would exceed the criteria for mortality established by Hinchey et al. (2006).

Wave and current interactions in shallow water (depths less than 3 feet) are particularly important to intertidal flora and fauna. For example, along the shallow edge of the tidal water, high suspended sediment concentrations may flow over a mudflat. This passage across the intertidal area potentially deposits large quantities of sediment and nutrients on upper mudflat areas, particularly at slack water (Christie and Dyner 1998, in Nightingale and Simenstad 2001b). These are part of the sedimentation and water transport processes that shape the geomorphology and consequently the plant and animal communities that rely on the shallow, soft sediment habitats of mud and sandflats (Nightingale and Simenstad 2001b).

Reducing wave energy from natural levels lowers the near bed shear stress, resulting in the deposition of finer sediments (Miller et al. 1977). Considering the large volume of fine-grained sediment supplied to western Washington waters (Downing 1983), even areas that are not part of an active littoral cell can receive a large amount of fine sediment. Deposition of large amounts of fine sediment can kill aquatic vegetation vital to nearshore HCP species. Recent work has shown that burying eelgrass at depths as little as 25 percent of the total plant height could decrease productivity and increase the mortality of eelgrass (Mills and Fonseca 2003). Eelgrass can also be discouraged from colonizing new areas with a high clay content as a result of recent sediment deposition (Koch 2001; Koch and Beer 2006).

7.4.2.2.2 Altered Current Velocities

In marine systems, reduced current velocities lead to the deposition of fine sediment (silt and clay) (Miller et al. 1977), particularly near major sources or sediment such as large rivers (Downing 1984). Altered sedimentation due to reduced current velocities could result in reduced spawning success, burial of organisms or habitats, and altered primary productivity. At the other extreme, strong currents can have significant impacts on both aquatic vegetation and the substrate it grows on or in. The relationship between flow velocity and a change is reflected through the boundary shear stress (Miller et al. 1977). Substrate and aquatic vegetation will be removed if the critical shear stress is exceeded.

The sensitivity of aquatic vegetation to altered current velocities is species-dependent and also dependent on other factors such as pollutant loading. Eelgrass and many other species of aquatic vegetation (e.g., bull kelp) require some water motion for survival (Fonseca and Bell 1998). It is likely that reduction in water velocity contributes to a lack of eelgrass.

In general, alterations in current velocities can contribute to modifications or removal of suitable habitats for fish in various lifestages. This alteration of habitat can inhibit the growth, survival, and fitness of various fish species. In addition, altered current velocities may also affect the exertion levels required for fish to move throughout the habitat. These changes could reduce the fitness required for migration or maintenance of normal behavioral functions or could result in direct mortality via direct burial and loss of suitable spawning or foraging habitat or indirect mortality resulting from impacts on prey species. Nearshore currents, even those in heavily altered environments, do not exceed the threshold for adult salmonid navigation, but high current velocities have been shown to exclude some small fishes from navigating nearshore waters (Michny and Deibel 1986; Schaffter et al. 1983). This would cause fragmentation of habitat for these species.

Alterations current velocity could alter transport and increase the mortality of planktonic spawn (e.g., rockfish). Altered currently velocity could directly impact those invertebrates that cannot tolerate extremely high shear stress or burial.

7.4.2.2.3 Altered Nearshore Circulation

Nearshore circulation is the flux of salt, water, and sediment associated with tidal and wave motion near the shoreline. In more exposed, sandy settings, such as the outer coast of Washington, nearshore circulation is dominated by the mechanics of wave breaking (Komar 1998). The effects of breaking waves are generally insignificant in Puget Sound (Finlayson 2006). In Puget Sound and near the mouth of large rivers such as the Columbia, tidal currents and freshwater input play a more important role in nearshore circulation. Tidal motions are rarely sufficient to mobilize material of gravel size or larger (Finlayson 2006), but they can mobilize fine sediments such as silt and clay, particularly in areas of high sediment supply (Nittrouer 1978).

Nearshore circulation patterns are a dominant characteristic that shapes the suitability of nearshore habitats for a range of HCP species. Alteration of nearshore circulation patterns can produce many of the same effects as alterations to wave energy or current velocities. Specifically, fish and invertebrate species that are planktonic breeders have been shown to produce spatially variable spawn that relies on the combination of wave motion, ambient currents, and circulation patterns for transport to and retention in productive nursery areas (Hernandez-Miranda et al. 2003; Rooper et al. 2006; Sinclair 1992). While studies on HCP species are lacking, virtually all of the purely marine HCP species such as herring, rockfish, pollock, and cod, have a planktonic egg and/or larval life-history stage dependent on wave and current patterns for transport to and/or retention in areas favorable for rearing. Developing larvae that are transported away from areas favorable for rearing before they are ready for life in open water face an increased risk of starvation and predation or, in the case of schooling pelagic species, may be permanently isolated from their spawning population (Sinclair 1992).

7.4.2.2.4 Altered Sediment Supply

Washington State contains thousands of miles of shorelines, including about 2,000 miles in Puget Sound alone. Much of this shoreline consists of poorly consolidated bluffs of glacial sediments faced with mixed sand and gravel, and some cobble. Erosion and occasional landslides on these bluffs provide the greater volume of sediment on Puget Sound shores compared with sediment delivered by rivers and streams (MacDonald et al. 1994). Local geomorphology, weather, fetch, and sediment sources determine the volume, timing, and direction of sediment transported past an individual beach. Shoreline sediment transport occurs along generally discrete segments ranging from a few hundred feet to several miles. These shoreline segments, called drift cells, include sediment source areas, sediment transport areas, and depositional areas. Sediment sources are the low and high bluffs that "feed" the beach with sand and gravel. Through littoral drift, sediments are transported along the shoreline. Actively eroding bluffs contribute to habitat conditions throughout the drift cell they support. The direction of drift within a drift cell may reverse between winter and summer as prevailing wind and wave directions change, causing sand to redistribute among beach areas (Cox et al. 1994).

Alteration of sediment transport patterns by HPA-permitted structures can present potential barriers to the natural processes that build spits and beaches and provide substrates required for plant propagation, fish and shellfish settlement and rearing, and forage fish spawning (Parametrix and Battelle 1996, Penttila 2000b, Thom et al. 1994, all in Nightingale and Simenstad 2001b; Thom and Shreffler 1996; Thom et al. 1996, 1997; Haas et al. 2002). Related wave energy and water transport alterations alter the size, distribution, and abundance of substrate and detrital materials required to maintain the nearshore food web (Thom et al. 1994). Pacific salmon, Pacific herring, surf smelt, sand lance, and a variety of other fish may be affected by habitat changes due to structures that affect littoral drift (Thom et al. 1994). Surf smelt, sand lance, and Pacific herring are important prey items for salmonids and other piscivorous species, therefore the impacts to these "forage fish" would extend up the food chain to other potentially covered species.

Alterations to littoral drift can also affect the beach profile (Thom et al. 1994). Changes in littoral drift that reduce sediment supply can make beach slopes steeper and increase erosional processes, especially in shorelines hardened by development resulting in a coarsening of the beach substrate, which can substantially interfere with the quality and quantity of intertidal forage fish spawning habitats (Thom et al. 1994).

Experimental investigations by Shteinman and Kamenir (1999, in Nightingale and Simenstad 2001b) demonstrate how the construction of jetties and other in-water structures can partially or completely disrupt the longshore transport process. In a natural hydraulic regime, size separation of sediments proceeds along the bottom slope with wave flow impact, and steep-sloped bottoms move larger sediments toward the shore, accumulating a thin nearshore strip along the shoreline. While smaller sediments were found to move toward deeper areas, where they accumulate or were further transported by currents, the opposite was found to occur on gentle bottom slopes, where smaller sediments accumulated near the shore and coarser sediments were moved toward the deeper areas.

One primary direct impact on fish and invertebrates from altered sediment supply is to alter the degree of turbidity in the nearshore environment (Au et al. 2004; Bash et al. 2001; Berry et al. 2003).

Benthic habitat may be impacted by alterations in natural sediment movement. For instance, a structure that interferes with littoral drift cells poses the risk of interference with the deposition of fine sediments to adjacent beaches that support beach spawning forage fish, such as surf smelt and sand lance (Nightingale and Simenstad 2001b). Limiting the fine sediments deposited to adjacent beaches also poses the risk of limiting the establishment of rooted vegetation, such as eelgrass, along submerged areas of adjacent shorelines and therefore the risk of reducing the available habitat for fish and shellfish species that rely on such vegetated habitats for spawning and rearing (Nightingale and Simenstad 2001b). The manner in which a structure is used by vessels determines additional effects of wave energy from vessel traffic and other effects such as vessel pollutant distribution or impacts to other adjacent shoreline structures (Nightingale and Simenstad 2001b).

Modifications to littoral drift have numerous indirect results, from substrate changes (Li and Komar 1992; Frihy and Komar 1993; El-Asmar and White 2002) to modifications in the distribution and delivery of groundwater to the coastal zone (Nakayama et al. 2007). The primary indirect impact of changing sediment supply by changing littoral drift, is to change the distribution of substrate within the littoral cell (Terich 1987). The loss of sediment to a drift cell results in a coarsening of the substrate, as fine-grained sediment is lost to deep portions of the basin by resuspension (Finlayson 2006) and not resupplied by freshly eroded bluff sediments. Because some drift cells can be extremely long (e.g., more than 20 miles long in the drift cell that extends between Seattle and Mukilteo on the northeastern shore of the main basin of Puget Sound [Terich 1987]), the effects of a modification can extend well beyond the primary activity area.

7.4.2.2.5 Altered Substrates

On the outer Washington coast, substrate is loose, deep, sandy, and unconsolidated. In these areas, increased or displaced wave energy associated with HPA-permitted structures creates wholesale erosion of the shoreline (Miller et al. 2001). In protected, previously glaciated areas, the basin topography is complex and the coarse nature of the substrate slows down erosion dramatically (Nordstrom 1992). In these locales, a lag deposit can easily form a near bedrock-like shoreline (e.g., Foulweather Beach [Finlayson 2006]).

HPA-permitted projects can alter substrate composition either directly, by purposely placing substrates that differ from those that occur naturally at a site, or indirectly, by altering wave and current energy, precluding the contribution of sediments from uplands, interfering with drift cell sediment transport and deposition, and introducing new substrates that result in shell-hash. Adding immobile substrate changes the mechanics of water motion on the shoreline, increasing wave reflection (Komar 1998; Finlayson 2006) and eliminating exchange of water into and out of the shoreline (Nakayama et al. 2007). The placement of structures can have the effect of increasing substrate scour or limiting deposition of sediments that provide suitable habitat for HCP species. Placement of fill associated with HPA-permitted structures alters the slope and depths of intertidal habitats.

Shoreline structures can modify species assemblages and habitats in the vicinity of the structures. Placement of riprap in the nearshore generally encourages a shift toward hard-substrate, often invasive, species (Wasson et al. 2005). These changes can directly affect the reproduction, growth, fitness, and survival of multiple life-history stages of HCP fish and invertebrate species, or result in indirect effects by affecting the viability and distribution of their prey species.

It is possible that coarser substrate could benefit some HCP species, particularly when the substrate is submerged and essentially acting as an artificial reef (Pondella and Stephens

1994). Placing rocky substrate in areas where it does not naturally occur can sometimes provide habitat for rockfish, a group of marine fish that are typically associated with hard, reef-like structure. Artificial reefs have been known to attract rockfish, but in the case of bank armoring, the potential benefits for rockfish are largely unknown. Some species of rockfish occur along shorelines and these could benefit, while other species typically do not occur along the immediate shoreline where bank protection structures would be placed.

Substrate is an important factor controlling the growth of aquatic vegetation in Puget Sound (Koch and Beer 2006). Placement of fill often results in a direct loss of vegetated shallow-water, nearshore habitat that juvenile salmonids use for rearing and migration. In general, the addition of immobile substrate decreases habitat suitability for juvenile salmonids and changes the character of the shoreline that was previously conducive to their use (e.g., Knudsen and Dilley 1987; Peters et al. 1998; Schaffter et al. 1983). While data indicate that habitat use of riprapped banks by yearling and older trout species may be equal to or higher than natural banks, use by subyearling trout, coho, and Chinook salmon is lower (Beamer and Garland et al. 2002; Hayman et al. 1996; Henderson 1998; Knudsen and Dilley 1987; Peters et al. 1998; Schmetterling et al. 2001; Weitkamp and Schadt 1982). In Elliott Bay, Toft et al. (2004) found similar densities of juvenile salmonids at sand/cobble beaches and riprap sites in settings where the riprap extended only into the upper intertidal zone. When riprap extended to the subtidal zone, higher densities of juvenile salmonids were found along riprap than at sand/cobble beaches. Toft et al. (2004) hypothesized that the shallow-water habitats preferred by juvenile salmonids were compressed along the highly modified shorelines with steep slopes; therefore, their snorkel observations were able to record all juvenile salmonids present. In comparison, at the sand/cobble beaches, the slopes were gentler, the zone of shallow water was much wider, and densities were therefore lower because the fish were more spread out.

Surf smelt and sand lance rely on substrates ranging in size from sand to gravel for spawning. Usual spawning substrates consist of fine gravel and coarse sand, typical of the pebble veneer found throughout Puget Sound (Finlayson 2006), with broken shells intermixed in some cases (Thom et al. 1994). Surf smelt are quite susceptible to the effects of alterations on shoreline processes (sediment supply, transport, and accretion) due to their reliance on specific beach profiles and substrate compositions for successful spawning (Penttila 1978). Surf smelt make no attempt to bury their demersal, adhesive eggs but rely on wave action to cover the eggs with a fine layer of substrate (Thom et al. 1994). Therefore, changing the wave environment may also change the survivability of surf smelt spawn or suitability of the site for future spawning habitat. The importance of substrate to spawning has also been empirically demonstrated in the closely related Japanese surf smelt (Hirose and Kawaguchi 1998).

Pacific sand lance spawn in the high intertidal zone, on substrates varying from sand to sandy gravel. Sand lance also rely on sandy substrates for burrowing at night. Like surf smelt, sand lance spawning is susceptible to the deleterious effects of littoral alterations because sand lance rely on a certain beach profile and specific substrate compositions (Penttila 1995).

Benthic communities, including invertebrate populations, are impacted by sediment alterations (Nightingale and Simenstad 2001b). For instance, the Olympia oyster is an epibenthic filter feeder found throughout the inland waters of Puget Sound, as well as in Willapa Bay and possibly Grays Harbor (WDNR 2006b). They occupy nearshore areas on mixed substrates with solid attachment surfaces and are found from 1 foot (0.3 meter [m]) above mean lower low water (MLLW) to 2 feet (0.6 m) below MLLW; the larvae settle onto hard substrate such as oyster shells and rocks (West 1997; Baker 1995, both in WDNR 2006b). Olympia oysters are intolerant of siltation and do best on firm substrates (WDNR 2006b).

Newcomb's littorine snail is found primarily in association with a narrow band of nearshore intertidal habitat that contains certain marsh plant species (Larsen et al. 1995). Newcomb's littorine snail may lose suitable habitat if large substrate is placed on top of substrate in the upper intertidal and supratidal areas that could otherwise support the snail's pickleweed (Salicornia virginica) vegetation habitat. Because detailed reproductive and habitat needs are not known, it might be conservatively assumed that Newcomb's littorine snail is also subject to smothering or substrate changes.

Mitigation may be available for the change from fine to coarse substrates (to some degree), as demonstrated by some projects that attempt to restore sand and gravel substrates to areas exhibiting large substrate. Monitoring in these projects has documented that epibenthic crustacean salmonid prey benefit from smaller substrate both in density and diversity of species (Parametrix 1985; Simenstad et al. 1991). Similarly, Thompson (1995) found an increase in hardshell clam abundance following beach graveling. [Peer review comment: Sobocinski (2003) and Sobocinski et al. (2004) would be better references for effects on invertebrates in Puget Sound, but these studies were not included.]

7.4.2.2.6 Altered Groundwater Input

Submarine groundwater discharge has been documented to play an important role in the circulation of fluids and nutrients on many coasts throughout the world (Gallardo and Marui 2006; Johannes 1980; Michael et al. 2005). Most work on the subject has focused on the nutrient load that these waters supply to the coastal ocean in sandy, exposed coastal environments (Gallardo and Marui 2006). The importance of groundwater seepage to the macroecology of the deep ocean (i.e., benthic environments) is well known (Kiel 2006). Both hydrothermal vents and cold seeps are known to be "hot spots" of biological activity, a direct result of groundwater discharge (Kelley et al. 2002; Kiel 2006). However, the direct impacts of submarine groundwater discharge on the nearshore environment are less clear. Solid concrete walls and steel piles that allow no groundwater penetration likely have increased impacts compared to more porous artificial substrates (e.g., riprap).

Several important effects have been documented in Puget Sound. For example, the lack of groundwater discharge can lead to increased substrate temperatures at comparable tidal elevations (Dale and Miller 2007; Rice 2006). Another loss of function is the removal of the seepage face at low tide (Gendron 2005). The correlation of the top of the seepage face to the landward limit of eelgrass beds has been anecdotally established in Puget Sound (Finlayson 2006). Although not demonstrated in a systematic study, the loss of the seepage face, as observed by Finlayson (2006) and Gendron (2005), would likely increase the risk of desiccation of aquatic plants. Desiccation has been found to be the dominant control on the growth of eelgrass (Zostera marina) in the Pacific Northwest (Boese et al. 2005).

Some species (such as the Olympia oyster) are known to take advantage of freshwater seeps along marine shorelines (West 1997; Couch and Hassler 1990). For species that are reliant upon freshwater seeps in the marine environment, groundwater impacts could potentially pose direct effects; however, the direct effect of submarine groundwater discharge on fish and invertebrates in nearshore areas is unclear (Simmons 1992).

7.4.2.3 Lacustrine Environments

The hydraulic and geomorphic modifications in lakes, natural or man-made, have the same six mechanisms of impact as the marine environment (i.e., altered wave energy, altered current velocities, altered nearshore circulation, a loss of groundwater input, altered sediment supply, and altered substrate composition), albeit on a different suite of species.

The impacts of HPA projects in lacustrine environments bear some similarity to impacts on marine environments. In both environments wave energy, and sediment recruitment and transport are altered. However, in lakes, these impacts are often exacerbated by differences in human-controlled water-level variability (in the case of reservoirs) and natural lake limnology (Wilcox et al. 2002). This inherent variability makes the differences between natural lakes and reservoirs less pronounced with respect to nearshore processes. However, there are other geomorphic differences with pronounced effects on habitat.

7.4.2.3.1 Lakes

Systematic studies of impacts on the habitat in the lakes in western Washington are extremely limited (Jones & Stokes 2006). Some analysis of habitat types and species distribution has been prepared as part of the development of shoreline master programs, but these only catalog species and activity types and do not provide information about their relation to one another.

Fish respond to habitat characteristics resulting from the association of shoreline and riparian zone modification. In a study of Wisconsin lakes, the habitat characteristics most influenced by this association were depth, substrate size and embeddedness, and amount of woody vegetation and macrophytes (Jennings et al. 1999). Species richness was greatest where there was complexity in this suite of factors.

Habitat in lacustrine environments is impacted by large, long-term, water-level fluctuations. These can be related to natural hydrologic changes; or, as is often true on Washington's largest lakes (e.g., Lake Washington), these fluctuations can be produced by human manipulation of inlets and outlets. The effects of such manipulations can manifest in a manner similar to natural changes and may complicate any assessment of impacts arising from human activities (Wilcox et al. 2002).

The physical processes discussed in depth under the Marine Environments section are considered to be relevant in lakes, recognizing that some differences occur (mostly apparent from previous work performed in the Great Lakes). The most important hydraulic and geomorphic differences between marine and lacustrine environments are in nearshore circulation, groundwater input, and short-period waves.

7.4.2.3.1.1 Nearshore circulation.

While wave energy in lakes is small relative to most marine beaches, wind plays an important role in driving the circulation (Rao and Schwab 2007). Unlike in the marine environment, where salinity is typically the most important water column constituent, temperature is the dominant factor in maintaining stratification in lakes. The absence of tides means that water level in lakes on the time scale of hours to days is stable, and any terraces that are formed are much more pronounced and discrete. Stratification and isolation of low dissolved oxygen zones are more easily achieved near lakeshores than marine shorelines, affecting all lake-dwelling HCP species that are sensitive to low dissolved oxygen.

7.4.2.3.1.2 Groundwater input.

Because lakes are fundamentally more connected to upland environments, the limiting nutrients in a lake are different than in a marine setting. However, just as in marine environments, benthic productivity and diversity have been linked to groundwater effluent (Hagerthey and Kerfoot 2005; Hunt et al. 2006). Unlike marine environments, lacustrine seeps have high productivity but low species diversity (Hagerthey and Kerfoot 2005; Hunt et al. 2006). Therefore, lacustrine deepwater species such as pygmy whitefish are less likely to be affected by groundwater alteration than marine pelagic species (e.g., rockfish) to the same alterations.

7.4.2.3.1.3 Short-period waves.

Because lakes are confined, all of their natural wave energy is generated from local winds. This makes all of the waves fetch-limited (Komar 1998). Fetch-limited waves have extremely short periods and small wave heights, compared to their open, marine counterparts. In this sense, lacustrine littoral processes are more similar to those found in Puget Sound (Finlayson 2006). Therefore, alterations to shorelines will not be felt as far from project activities as if they were to occur in the marine environment. The size of area affected by lakeshore development has relevance for sockeye spawning habitat (WDNR 2006a).

While littoral processes are most conspicuous in marine waters, they can occur along lake shores as well, where fetch and wind speed combine to produce waves and subsequent longshore currents strong enough to move shoreline sediments.

7.4.2.3.2 Reservoirs

Human-operated reservoirs present special issues. Reservoirs are morphologically, biologically, and hydrologically dissimilar from natural lakes. Morphologically, lakes are often deepest near the middle, whilst reservoirs are typically deepest at the downstream end. This difference has implications for current strength and direction. The plan view of reservoirs can be quite variable, depending on the degree of confinement, but the length of the shoreline is often longer than that of a natural lake. Also, the extent of shoreline development is much greater than in natural lakes because annual drawdown exposes a larger area to shore processes by expanding the area alongshore exposed to wave breaking (Baxter 1977). The location and nature of depositional forms are highly variable with reservoir morphometry, incoming sediment load, and reservoir operation. Reservoirs are also subject to density or turbidity currents resulting from differences in temperature or sediment concentration between inflows and reservoir waters (Snyder et al. 2006). Mixing zones between the water sources influence the usage of reservoir areas by fishes.

Reservoir environments can lack natural habitat due to loss of riparian forest because of flooding, siltation of rocky shorelines, and a paucity of aquatic vegetation resulting from fluctuating water levels (Prince and Maughan 1978). Dependent on reservoir operations, drawdown and filling cycles can re-entrain silty deposits in littoral areas. When jetties, barbs, or breakwaters are constructed, the combined footprint of fill materials and pilings obliterates physical habitat and can exacerbate the degradation of littoral areas.

7.4.2.3.2.1 Nearshore Circulation

The presence of structures such as marinas that disrupt either the movement of fishes within the littoral zone or nearshore circulation may add to the inherent temperature stressor present in a reservoir. Littoral zones separated from the larger reservoir body may become significantly warmer and exhibit larger diel temperature fluctuations (Kahler et al. 2000). Similarly, structures that extend into the mixing zone may also present a physical barrier to the movement of fishes in and out of these zones. The presence of a jetty was found to restrict circulation between a discharge stream and receiving water (Altayaran and Madany 1992).

7.4.3 Activity-Specific Effects

7.4.3.1 Overwater Structures: Docks, Piers, Marinas and Shipping Terminals

Impacts on fish species associated with marina/terminal structures include decreased growth and survival, decreased developmental and migratory fitness, and direct mortality. Migration timing may also be affected for some fish species, ultimately affecting reproductive success. Marinas have been found to attract large populations of juvenile salmon and baitfish and provide permanent habitat for a variety of other fish (Cardwell et al. 1978; Heiser and Finn 1970; Penttila and Aguero 1978; Thom et al. 1988; Weitkamp and Schadt 1982). This attraction is likely due to the low hydraulic energy similarities between a marina environment and a natural embayment (Cardwell and Koons 1981).

Increased impervious surfaces associated with marinas and terminals are unlikely to produce damaging effects on peak and base flow conditions of the adjacent water bodies. Marinas and terminals are typically developed on larger rivers, lakes, and marine waters. Such water bodies are considered insensitive to the relatively small increase in impervious surface area and to the effects of flow perturbation imposed by impervious surfaces. This exemption applies in ESA consultations as well (WSDOT 2006d).

Depending on the geomorphology, current transport processes, and climatic conditions of a specific area, overwater structures have the potential to alter important habitat-building processes (Nightingale and Simenstad 2001b) such as sedmentation and water transport.

One of the most profound changes produced by marinas is to change the shoreline from a dynamic, loose surface to a rigid, immobile one. Although there are distinct differences between artificial substrates placed in marina construction, over time they all behave like bedrock shorelines similar to extremely coarse-clastic beaches in Puget Sound (Finlayson 2006). The primary difference between these installations is whether they permit exchange of groundwater with the sea. Submarine groundwater discharge has been documented to play an important role in the circulation of fluid and nutrients on many coasts throughout the world (Gallardo and Marui 2006; Johannes 1980; Michael et al. 2005;). When marinas are installed, the substructure that interrupts the free exchange of groundwater between the sea and the uplands has been shown to have adverse effects on nearshore ecosystems (Nakayama et al. 2007).

7.4.3.1.1 Impacts to Littoral Drift

In-water structures such as piers and pilings have the potential to block or divert littoral currents. Alteration of littoral currents can cause sediment deposition and reduce beach nourishment down-current from the structure (Thom et al. 1994). Changes in beach nourishment and sediment deposition can in turn alter benthic and epibenthic communities, as well as bank erosion rates (Thom et al. 1994). The significance of these effects depends on the location and orientation of the structures (Thom et al. 1994). Closely spaced pilings can collect sediment along the up-current side (Nightingale and Simenstad 2001b), but widely spaced pilings allow currents to flow freely and sediment transport is essentially unaffected (Nightingale and Simenstad 2001b). For pile groupings, the magnitude of bed scour depends on the pile diameter, the spacing between piles, the number of pile rows and their staggering, and the alignment of pile rows relative to the principal direction of flow (Salim and Jones 1999; Smith 1999). Ratte and Salo (1985) and Penttila and Doty (1990) found that pilings associated with shoreline structures changed the flow of water around the pilings and over the substrate, thereby altering the bathymetry of the substrate and the flow of water in the immediate area.

Open pile structures tend to interfere less with sediment transport. Structures located in low-energy areas that block littoral drift tend to fill in with sediment and require maintenance dredging.

Marinas are specifically designed to diminish ambient wave energy and current velocity so that maritime activities can be conducted. In the process of creating a shoreline that suits this purpose, ambient waves are reflected (Wurjanto and Kobayashi 1993), diffracted (Melo and Guza 1991), and refracted (Komar 1998). Vessel traffic associated with the addition of a marina can interact with these artificial boundaries, causing a significant increase in wave energy even in some places inside the marina (Tarela and Menendez 2002; Isaacson et al. 1996).

Numerous studies have been performed that have attempted to manipulate the incoming wave energy to reduce reflected, refracted, and diffracted wave trains from entering the port or marina; in fact, there are entire journals dedicated to this topic (e.g., Journal of Waterway, Port, Coastal and Ocean Engineering). These alterations typically result in the construction of a series of jetties, groins, and breakwaters. Regardless of the nature of the alterations, the modified relationship between topography and wave energy results in a shoreline that is out of equilibrium with natural shoreline processes (Komar 1998). As a result, wave energy artificially accumulates in some areas and is diminished in others. For example, due to reduced wave energy, marinas are likely to experience accumulations of fine sediments in excess of levels that existed prior to the modification of the site.

Pilings, navigation dredging, and prop wash associated with the construction, operation, and repair of marinas/terminals alter both the bathymetry and littoral drift of the area around and under such structures, both in exposed (Komar 1998) and sheltered settings (NRC 2001).

7.4.3.1.2 Substrate Alteration: Shell-Hash

Pilings can alter adjacent substrates, with increased shell-hash deposition from piling communities and changes to substrate bathymetry (Haas et al. 2002; Shreffler and Moursund 1999; Blanton et al. 2001). Pilings provide surface area for encrusting communities of mussels and other sessile organisms such as seastars that prey upon the shellfish attached to the dock. The resulting shell-hash accumulated at the base of the piling alters adjacent substrates and changes the substrate bathymetry (Blanton et al. 2001; Haas et al. 2002; Parametrix 1996; Penttila and Doty 1990; Southard et al. 2006). These changes in substrate type can also change the nature of the flora and fauna at a given site. In the case of pilings, native dominant communities typically associated with sand, gravel, mud, sand, and seagrass substrates are replaced by those communities associated with shell-hash substrates. Shell-hash is a prime settling habitat for Dungeness crab. Both crab and seastar foraging activity can disrupt eelgrass and retard recruitment. Crabs burrowing into the substrate to avoid predation may significantly inhibit eelgrass recruitment (Thom and Shreffler 1996). Such disturbance of seagrass meadows by animal foraging is also reported elsewhere (Baldwin and Lovvorn 1994; Camp et al. 1973; Orth 1975; Williams 1994).

7.4.3.1.3 Effects on wave direction and intensity

Overwater structures and piling can affect wave direction and intensity. The effects of piers and pilings on wave action depend on spacing, orientation, and number of pilings, as well as depth and proximity to shore (Fresh 1998, in Nightingale and Simenstad 2001b; Nightingale and Simenstad 2001b). Widely spaced piles in deep water have relatively little effect, as waves refract around them (Nightingale and Simenstad 2001b). In contrast, a series of pilings can reflect waves, resulting in reduced littoral currents (Nightingale and Simenstad 2001b). Floating structures can also attenuate waves and alter the intensity of wave action that cause and maintain littoral drift (Nightingale and Simenstad 2001b). The effectiveness of a floating structure as a wave attenuator depends on the shape, dimensions, and orientation of the structure (Cox et al. 1994).

Overwater structures normally have little capacity to alter channel gradient.

7.4.3.1.4 Vessel Wake and Prop Wash

Wakes from large commercial vessels have profound effect on shallow water habitats. Wave energy striking the beach/bank causes redistribution/suspension of sediments, bank erosion, displacement of shoreline vegetation and wood debris, and disruption to flora and associated fauna. While this has not been studied extensively, there is information available from the studies of ferry wakes in Rich Passage. The frequency of ferry traffic, sometimes every half hour throughout the day, makes prop wash effects at ferry terminals an exception to other docks. Prop wash and benthic disturbance by ferries are well documented for ferry terminals (Blanton et al. 2001; Francisco 1995; Haas et al. 2002; Michelsen et al. 1999; Olson et al. 1997; Parametrix 1996; Shreffler and Gardiner 1999; Thom et al. 1997; Thom and Shreffler 1996). Carrasquero (2001) and Kahler et al. (2000) provide a review of what is known about shoreline and overwater structure impacts in freshwater environments.

Prop wash and waves are also known to be a primary cause of shoreline erosion (Gatto and Doe 1987; Mason et al. 1993). The number of boats in a given area has been correlated with wave height (Bhowmilk et al. 1991), with areas of high boat traffic exhibiting increased levels of shoreline erosion. Although it is difficult to quantify boat wake contributions to shoreline erosion, boat traffic has been found to contribute up to 50 percent of the factors responsible for shoreline erosion in small rivers less than 2,000 feet wide (Hurst and Brebner 1969). Sutherland and Ogle (1975) found prop wash and increased turbidity from jet boats to decrease salmon egg survival by 40 percent. In addition to turbidity, direct contact with spawning substrate can cause mortality.

7.4.3.2 Navigation/Maintenance Dredging

Dredging may occur in navigation channels, in marinas, or near terminals. Navigation or maintenance dredging is by far the most frequent form of dredging in Washington State.

Dredging in marine environments converts intertidal habitat to subtidal habitat and shallower subtidal habitats to deeper subtidal habitats. Dredging affects the plant and animal assemblages that are uniquely adapted to the particular light, current, and substrate regimes of intertidal areas. By altering bathymetry and bottom substrates, such conversions produce a "trade-off" of intertidal and shallow-subtidal communities for deeper, subtidal communities.

In lacustrine environments, dredging converts shallow-water littoral habitats into deeper water environments and may create a steeper bathymetric transition. This change in habitat characteristics may change the size and species distribution of fish in the localized environment, altering predator/prey dynamics.

The effects of dredging on riverine environments are more complex still, because localized alteration of channel morphology can lead to dynamic shifts in channel form as the system adjusts to the changed conditions. These effects can extend a considerable distance beyond the bounds of the original dredging project.

Construction and maintenance of shipping access to marinas have been shown to both increase (da Silva and Duck 2001) and decrease (Sherwood et al. 1990) tidal prisms, depending on the characteristics of the tides and freshwater input and the nature and geometry of the alterations. The reduction of the tidal prism, as documented on the Columbia River (Sherwood et al. 1990), can eliminate entire habitats from being exposed to tidal action. In addition to stranding areas from marine influence, reduction in tidal motions can increase stratification and limit the vertical mobility of nutrients and dissolved oxygen (Mickett et al. 2004). Recent work has shown that there is a complex interplay among these phenomena and the primary productivity of nearshore waters; however, more dramatic consequences could occur in naturally mixing-limited waters of Puget Sound. Aside from the obvious impacts on inundation of adjacent landowners, increasing tidal prisms can expose aquatic species (both fish and invertebrates) to polluted sediments, such as those found at Superfund sites, potentially resulting in long-term contaminant related impacts.

There are several different means by which dredging affects fish and invertebrates, the most significant being alteration of bathymetry and substrate composition.

Large channel deepening projects can markedly alter ecological relationships through the change of freshwater inflow, tidal circulation, estuarine flushing, and freshwater and saltwater mixing. 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 comparison between dredged and undredged areas 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 decreased from about 90 fish per tow to about 3 fish per tow and from eight species to five species.

Depending on site characteristics, maintenance dredging may occur annually or at intervals of 10 years or longer. These different dredging timelines 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 on invertebrate communities to be from negligible to severe, with impacts ranging from short to long term. In experiments conducted in sheltered sand flats, the benthic community recovered from lower intensity disturbance (i.e., sediment removal to a depth of 3.9 inches [10 cm]) within 64 days, whereas recovery from higher intensity disturbance (i.e., sediment removal to a 7.9-inch [20-cm] depth) required 208 days postdisturbance (Dernie et al 2002).

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 at a disposal site between June 1989 (predisposal) and June 1990 (postdisposal). Recolonization could have occurred by invertebrates burrowing up through newly deposited sediments or recruitment from surrounding areas (Richardson et al. 1977).

7.4.3.3 Bank Protection and Shoreline Modifications

In marine, riverine, and lacustrine systems, a reason for installing many bank protection structures and shoreline modifications is to alter hydraulic and/or geomorphic processes. Bank protection structures such as bulkheads and revetments are constructed parallel to the shore. Shoreline modifications such as jetties, groins, and breakwaters, project out from the shore.

Structures built to prevent bank erosion can alter the contribution of sediment to the aquatic environment. Structures that are constructed to protect upland properties from erosion can entrain fine sediments during construction, modify the substrate available to species for spawning and rearing by blocking the contribution of sediments and LWD to the shoreline from the uplands or from upstream areas (NMFS 2003), and increase the scouring of substrates. This scouring action can affect downstream or downcurrent habitats by transporting and depositing fine sediments, thereby compromising spawning habitat, burying potentially covered species, or increasing embeddedness of occupied habitats. It can also dramatically modify the types and abundance of substrates available to support aquatic vegetation.

7.4.3.3.1 Bank Protection in Riverine Systems

The intent of adding non-erodible substrate to a riverine system (e.g., riprap) is to stabilize channels and limit natural fluvial processes. The anthropogenic alteration of the river environment through the addition of bank protection or shoreline modification structures can disrupt the balance of the channel processes that form and maintain habitats throughout a river system (Fischenich and Allen 2000). Such structures have direct effects on river processes because they modify river channels and are designed to limit or prevent natural channel processes along the length of the structure. The disruption of channel processes is the most significant mechanism of impact generated by bank protection projects. Bank protection structures in or adjacent to channels can produce the following alterations to the channel processes and morphology:

- Channel straightening and shortening

- Channel narrowing
- Reduced habitat complexity
- Channel incision/increased scour
- Substrate coarsening
- Channel braiding/increased deposition
- Decreased floodplain connectivity
- Decreased channel migration and side channel creation
- Reduced LWD and organic material recruitment
- Reduced gravel recruitment
- Disrupted flow through the hyporheic zone[1]

7.4.3.3.1.1 Changes in Channel Hydraulics and Geomorphology

Bank protection structures, particularly those that are designed for flood control tend to straighten and shorten channels (Brookes 1988, in Bolton and Shellberg 2001). If a bank protection structure is placed below the ordinary high water level (OHWL), the channel is effectively narrowed or constrained, and disconnected from the floodplain. These types of changes to the channel result in reduced habitat complexity, especially when the removal of logs or snags will coincide with the placement of the structure (Bolton and Shellberg 2001). For example, in the Skagit River, a comparison of protected conditions to natural riverbank conditions showed that habitat complexity and off-channel refugia were higher along natural banks (Hayman et al. 1996). River sections with extensive bank protection structures generally tend to create primarily glide habitat with poorly sorted substrates (Bolton and Shellberg 2001).

An associated outcome of the disconnected floodplain is the limitation of lateral channel migration. The lateral migration of rivers, as well as riparian succession, is a necessary process for the maintenance of appropriate energy levels in a system, and thus promotes habitat diversity (Fischenich 2001). Reduction in channel migration tends to limit the creation of complex main channel and side channel habitats (Beamer et al. 2005). If a bank protection structure is installed when the channel alignment is unstable, the structure will attempt to maintain that alignment (Saldi-Caromile et al. 2004), which may reduce the structure's effectiveness.

Bank protection structures that constrict the channel generally lead to greater increases in velocities along the length of the structure compared to structures that do not constrict the channel (Fischenich 2001). Channel constriction can lead to incision or downcutting of the channel as erosion occurs across the entire channel bed at the constriction (Cramer et al. 2003). The intrinsic ability of flow to transport sediment increases in a deepened channel, which can result in a coarsening of substrates within and downstream of a constricted section (Naiman and Bilby 1998). Such increases usually have no effect on

[1] Hyporheic zone is a broad term that defines the "saturated interstitial areas beneath the stream bed and into stream banks that contain some proportion of channel water or that have been altered by channel water infiltration (advection)" (White 1993, in Bolton and Shellberg 2001).

the average cross-sectional velocity; rather, there is a redistribution of velocities, such that higher velocities occur adjacent to the structure (Fischenich 2001).

Channel incision also occurs if the bank protection structure or material (e.g., riprap) reduces channel roughness and generates an increase in water velocity and turbulence near the bank protection structure (Fischenich 2001; Miller et al. 2001). The increased scour and channel incision usually occurs along the toe of the structure and/or immediately downstream (Fischenich 2003), and may extend into the stream approximately two to three times the scour depth (Fischenich 2001). Scour may occur as a short-term or long-term outcome of having a bank protection structure in place, but the impacts tend to persist over an extended period of time (Fischenich 2001). Hardened banks that replace riparian vegetation can increase the flow velocity and potential for scour and substrate coarsening through a reduction in hydraulic roughness compared to vegetated conditions (Millar and Quick 1998). Because of their stability and low hydraulic roughness, hardened banks can act as natural attractors for channels and result in a static channel form lacking habitat diversity (Dykaar and Wigington 2000).

These impacts to channel processes often occur in areas beyond the immediate extent of a bank protection structure. The type and extent of the alterations depend upon the geomorphic and hydrologic setting of the river (Bolton and Shellberg 2001). For example, an alluvial river system with a channel bed and banks comprised of sediments will more easily incise and scour than a channel over bedrock.

Additional sediment movement associated with increased scour and channel incision can result in increased volumes of sediment deposited at some distance downstream. The downstream river setting, including slope, floodplain width, and flow volume, as well as the volume of bedload material transported downstream, influences where the material is deposited and what impacts it may have on habitat and species. Similarly, areas upstream of bank protection structures may also encounter sediment deposition if associated channel narrowing backs up water to some extent. Such sediment deposition could contribute to upstream river instability, which could threaten land, including the parcels with bank protection.

Bank armoring with non-erodible substrate can coarsen the bed by directly adding material coarser than the ambient bed and through the attendant effects of channel homogenization. Substrates larger than those occurring naturally are often placed in or along water bodies as part of bank protection projects. Placement of large rock that remains stationary (i.e., is non-erodible) during high flows is more often a component of hard bank protection techniques than soft or integrated techniques. The size of the material placed, the substrate covered, and other environmental conditions determine the degree to which substrate-dependent functions are impacted. Because potentially covered species depend upon aquatic substrates for life history and habitat functions, impacts to substrates ultimately affect the species' distribution and ability to grow and survive. Available studies on the impacts of adding non-erodible substrates are primarily focused on the effects of riprap on salmonids.

7.4.3.3.1.2 Changes in Habitat

The addition of large, angular rock to banks is known to affect salmonid habitat and abundance. Knudsen and Dilley (1987) found that abundance of juvenile salmonids was reduced by bank reinforcement activities due to a loss of structural diversity and that these reductions were correlated with the severity of habitat alteration, the size of the stream, and the size of the fish. In a study from California, the primary cause for the decline of salmon in the Sacramento River was linked to the loss of spawning gravels normally derived from bank erosion before riprap bank stabilization (Buer et al. 1984). A comparative study in several western Washington streams found that salmon abundance was less along banks modified with riprap compared to natural banks containing vegetation and woody debris (Peters et al. 1998). Studies comparing the abundance of fish in areas of different size riprap correlate greater fish densities with larger rock (Beamer and Henderson 1998; Lister et al. 1995; Garland et al. 2002). Lister et al. (1995) found that juvenile salmonid densities were greater along banks with riprap greater than 1 foot (30 cm) median diameter compared to natural banks composed of cobble–boulder material presumably due to the cover provided by the relatively larger interstitial spaces created by the coarser bank protection. Indirect effects on fish from bank hardening (i.e., loss of temperature moderation and potential cover) can occur due to the replacement of riparian vegetation with rock (Chapman and Knudsen 1980).

The addition of large substrate for bank protection would generally negatively impact habitat for cold-water species that use shallow margin habitats for feeding and refuge (Fischenich 2003), but would positively impact species that are associated with rock structure and interstitial spaces. Generally, species benefiting from the placement of rock may be non-native species that are piscivorous (e.g., brook trout) (Schmetterling et al. 2001).

In general, the addition of artificial substrates will decrease habitat suitability for juvenile salmonids and will change the character of the shoreline that was previously conducive to their use (Knudsen and Dilley 1987; Li et al. 1984; Peters et al. 1998; Schaeffter et al. 1983, in USFWS 2000), whereas for fish found in the interstices or relying on prey found there (e.g., sculpin), artificial substrates can increase habitat availability and usage (Li et al. 1984). While data indicate habitat use of riprapped banks by yearling and older trout species may be equal to or higher than natural banks, use by sub-yearling trout, coho, and Chinook salmon is lower (Beamer and Henderson 1998; Garland et al. 2002; Hayman et al. 1996; Knudsen and Dilley 1987; Peters et al. 1998; Schmetterling et al. 2001; Weitkamp and Schadt 1982). Knudsen and Dilley (1987) found that abundance of juvenile salmonids was reduced by bank reinforcement activities due to a loss of structural diversity and that these reductions were correlated with the severity of habitat alteration, the size of the stream, and the size of the fish. Size of material is also relevant, as greater fish densities have been generally correlated with larger rock (Beamer and Garland et al. 2002; Henderson 1998; Lister et al. 1995). Lister et al. (1995) found that salmonid densities were greater along banks with riprap greater than 1 foot (30 cm) median diameter compared to natural banks composed of cobble-boulder material.

Kahler et al. (2000) noted that bulkheads that are nearly vertical and constructed of large boulders with large interstitial spaces can provide concealment to piscivores. No studies documenting the occurrence of increased predation of juvenile salmonids in riprap areas were identified. However, a study of fish diets in the Willamette River (Portland, Oregon) found that smallmouth bass (Micropterus dolomieui), yellow perch (Perca flavescens), and other centrarchids captured at riprap locations (although not likely to occupy interstitial spaces) were more likely to have fish in their stomachs than the same species captured along natural shorelines (Vile et al. 2004). Sculpins are piscivores that occupy interstitial spaces and, when larger than approximately 2 inches (50 millimeters [mm]), can prey upon juvenile salmonids (Tabor et al. 1998). Based on the Tabor et al. (1998) observation that more and larger sculpin were found in locations with larger substrates, Kahler et al. (2000) infers that increased predation to juvenile salmonids may occur in those areas.

These patterns in juvenile salmonid habitat use are generally attributed to the impacts of the bank protection material on localized hydraulics, substrate, and available food and cover for fish at stream sites where hard bank protection materials are used. Rock riprap can disrupt flows, reduce food delivery, and create difficult swimming for small fish (Michny and Deibel 1986; Schaffter et al. 1983). In addition, riprap shorelines will be less likely than natural shorelines to retain wood at the bank for increased habitat structure (Schmetterling et al. 2001). Several researchers (Beamer and Henderson 1998; Michny and Deibel 1986; Peters et al. 1998; Schaffter et al. 1983) found that where large, complex wood deposits have been either maintained or incorporated into riprap, fish densities were higher than densities at sites without such structures. The mechanisms affecting why yearling salmonids occur in higher numbers in riprap areas are not well understood.

Little has been documented regarding impacts to invertebrates from bank protection and shoreline stabilization projects. The addition of riprap usually results in an increase in macroinvertebrate biomass and density of those species using interstices and hard substrates (Fischenich 2003). The Western ridged mussel lives in small substrates that would be less available in areas where bank protection structures add large substrate.

7.4.3.3.1.3 Altered Groundwater/Surface Water Exchange

Bank protection structures can disrupt exchange of groundwater and surface water in the hyporheic zone by creating a physical barrier (Fischenich 2003). Only some sorts of bank protection require the use of structures such as pilings or other impermeable structures that impede the exchange of hyporheic water with main river channels. When such structures are necessary, ecological impacts associated with the loss of exchange of hyporheic flow occur.

7.4.3.3.2 Bank Protection in Marine Systems

Bank armoring is sometimes placed in marine environments to alter wave energy that would otherwise cause erosion of a stretch of shoreline. However, it has also been observed that bank protection can, in the long run, increase or displace erosion. Bank protection may alter nearshore circulation in ways that are similar to (but generally less pronounced than) alterations caused by shoreline modifications such as jetties, breakwaters, groins and bank barbs. Bank protection structures and other artificial shoreline features can affect littoral drift through their influence on sediment supply and sediment transport.

7.4.3.3.2.1 Changes in Hydraulics and Geomorphology

Bank protection structures may decrease complexity of the shoreline by altering wave action in the littoral zone. Wave action creates complex littoral habitat by removing fine or silty sediments (Beauchamp et al. 1994). At marine shorelines, bulkheads have been shown to sort and coarsen existing substrate by increasing turbulence, wave reflection, and scour in front of the structure (e.g., Williams and Thom 2001). This often leads to a need for further supplemental armoring of foreshore and adjacent beach areas (Cox et al. 1994), often occurring in the form of additional riprap at the toe of the bulkhead.

Revetments tend to have slightly reduced impacts due to altered wave energy relative to vertical bulkheads because of the materials used and their configuration. Revetments are generally constructed of non-erosive material (e.g., riprap or quarry spall) that varies in size depending on water levels and wave energy of a specific site and are usually built to a slope of 1.5 or 2 horizontal units to every 1 vertical unit (Williams and Thom 2001). Because they slope, revetments can partially attenuate wave energy (the remaining energy is reflected) and water can filter through the rock material in the swash zone, protecting the underlying beach sediment. Although revetments can attenuate wave energy, sediment supply is still isolated from the littoral drift system, and the material used in the revetment replaces or covers naturally occurring substrates. However, revetments generally occupy a much larger footprint on the beach/shoreline than vertical structures.

Both during and after construction, bank protection projects have the potential to directly or indirectly modify substrate conditions. In marine environments, bank protection can cut off naturally eroding uplands (feeder bluffs) from beaches, potentially resulting in changes in substrate, size, composition, distribution of aquatic vegetation, and beach angle. A structure such as a bulkhead, if functioning correctly, prevents potential bank and bluff material from supplying the aquatic system (Johannessen et al. 2005). Along the Puget Sound shoreline, this disconnection or impoundment of natural sediment sources is possibly the most significant impact of shoreline protection measures (MacDonald et al. 1994).

Studies on impacts from bank protection structures have quantitatively measured conditions in front of a bulkhead and at adjacent un-bulkheaded shores and have shown that in front of a bulkhead, the suspended sediment volume and littoral drift rate all increased substantially compared to unarmored shores, which resulted in beach scouring and lowering along the armored shores studied.(Miles et al. 2001). Hard shoreline structures in the wave zone reflect wave energy with little attenuation of power (Miles et al. 2001). Bank protection structures that inhibit the erosion of feeder bluffs or transport of sediment stored high on the beach would cause erosion of material on the beach at the face of the structure and from the beach downdrift of the structure. As a result, beaches located in front of, and downdrift from, shoreline armoring can experience coarsening of the substrate, beach lowering, and beach narrowing (Anchor Environmental et al. 2002; Dean 1986; Everts 1985; Galster and Schwartz 1990; Johannessen et al. 2005; MacDonald et al. 1994; Zelo et al. 2000). The negative impact of sediment impoundment is most pronounced when armoring occurs along actively eroding bluffs, because these areas supply beach substrate throughout the length of the drift cells they support (MacDonald et al. 1994).

Silvester (1977, in Gabriel and Terich 2005) found that the presence of seawalls doubled the littoral energy applied to the sediment, which led to increased scour downdrift. As a result, more small sediment (e.g., sand and gravel) is entrained and moved than would occur along a natural shoreline that attenuates wave energy. This scouring impact is generally greater in vertical structures, such as bulkheads, compared to artificially or naturally sloped beaches (Zelo et al. 2000). Vertical structures also tend to focus wave energy on adjacent beach and backshore areas, which could contribute to erosion in areas downdrift of the bulkhead (MacDonald et al. 1994). Shoreline hardening manifests itself by a loss of the pebble veneer that is common throughout much of Puget Sound (Finlayson 2006). This process is similar to what has occurred on the urbanized shorelines throughout the Great Lakes (Chrzastowski and Thompson 1994).

One example of the impacts of bank protection on sediment supply and transport conditions is Seahurst Park in central Puget Sound (Burien, Washington). At Seahurst Park, the placement of bank protection structures in the 1970s resulted in dramatic changes to the habitat conditions in the park and reduced the amount of sand and gravel available throughout the 11-mile-long drift cell. The park shoreline was armored using a combination of stacked gabions, vertical concrete bulkhead, and riprap. A survey conducted in 2001 demonstrated that since shoreline armoring, beach elevations in the park have dropped approximately 3 to 4 feet. Further, the former sand, gravel, and small cobble beach now consists of larger substrates because the bank protection structures caused an increase in the erosive energy of waves moving sediment offshore and disconnection of the beach from primary sediment sources (bluffs) (Anchor Environmental et al. 2002).

Soft shore protection structures tend to absorb and attenuate wave energy better than hard structures by mimicking natural processes (Johannessen et al. 2005). Soft shore protection structures that maintain more natural slopes and materials that can be reshaped (e.g., an enhanced gravel berm) can absorb incoming wave water and attenuate the energy before the water percolates out gradually.

There are certain situations in which bank protection structures, particularly soft-shore techniques, can benefit habitat conditions by limiting sediment introduction. These benefits occur in settings where there is an overabundance of sediments and/or the sediment sources being disconnected are particularly fine sediments.

7.4.3.3.2.2 Changes in Habitat

Damage to surf smelt spawning areas has been documented in the presence of bulkheads in Hood Canal (Herrera 2005; Penttila 1978, in Thom et al. 1994).

Ahn and Choi (1998) found that in the presence of a new seawall, sediment grain size became significantly coarser and some shifts in dominance of abundant species occurred, including a tenfold increase in total abundance and biomass of the surf clam (Mactra veneriformes).

An active debate exists in the scientific community as to whether protective structures associated with marinas are as productive and diverse as natural hard-rock shorelines, particularly in the Adriatic Sea west of Italy (Bacchiocchi and Airoldi 2003; Bulleri et al. 2006; Guidetti et al. 2005). These studies in the Adriatic Sea have shown that maritime structures caused elimination of mobile, sandy habitats; weighted abundances in piscivores and urchins; and decreased abundances of native species that prefer more mobile substrates (Guidetti et al. 2005). Although species distributions are clearly different in Italy than in Washington State, the steep, paraglacial landscape and relatively short period and locally generated waves make hydraulic and geomorphic variables essentially identical (Finlayson 2006).

7.4.3.3.3 Bank Protection in Lacustrine Systems

Bank protection projects have the potential to directly or indirectly modify substrate conditions both during and after construction. In lake environments, waves striking shorelines at an angle transports sediment parallel to shore in the direction of the prevailing wind (Jacobsen and Schwartz 1981). Bank protection structures can impact sediment transport through changes in wave energy reflection and attenuation.

In both natural lacustrine systems and in reservoirs, bank protection can remove physical habitat and can exacerbate the degradation of littoral areas. Wave action may be a source of desirable spawning substrate. Kokanee salmon were observed to prefer spawning locations characterized by wave action, steep slopes, and an abundance of small, loose particles in Flaming Gorge Reservoir, Wyoming (Gipson and Hubert 1993). Lorang et al. (1993) observed that docks and seawalls intercepted transported gravels in Flathead Lake, Montana, as regulated lake levels rose and fell from early spring to late summer.

7.4.3.3.4 Dikes and Levees

Dikes and levees alter the hydraulic and geomorphic properties of the environment where they are located. In a riverine system, dikes and levees reduce a river's connection with its floodplain and increase peak flows (Liu et al. 2004). This can lead to habitat isolation and strand fish in isolated pools without connection to the mainstem, and prevent access to low velocity refuge areas (Bolton and Shellberg 2001).

Some bank protection structures, especially levees, are designed to increase flood capacity in a more vertical than horizontal configuration, so the flow confined between the levees during high flows tends to be deeper and faster than if the floodplain could be accessed. Higher velocities and deeper water compared to conditions prior to construction tends to lead to increased erosion downstream (Bolton and Shellberg 2001). Bank protection structures intended to address bank erosion at the point of installation often result in the long-term reverse effect of increasing scour via alterations to hydraulics. Levees typically confine river flows to straightened channels, reducing channel sinuosity and altering channel geometry and sediment transport.

In tidal marshes, impacts are similar and include changes in channel geometry, sediment transport, and flow regime. In addition, due to their proximity to tidal areas, dikes located in nearshore sloughs and estuaries can lead to changes in wave energy, current velocities, and nearshore circulation. In a study of the Skagit River delta, dikes caused a reduction in tidal flushing, which increased sedimentation within the tidal area and reduced channel sinuosity (Hood 2004). Furthermore, loss of floodplain area to dikes prevents flood energy dissipation over the marsh surface, causing the mean channel width to increase and sinuosity to decrease (Hood 2004).

A disconnected floodplain and single stream channel are often goals of bank protection, despite the fact that an active floodplain connection plays a critical role in the dynamic equilibrium of rivers. Bank protection structures typically restrict the inundation of the floodplain. In the case of levees, which are designed and built for the purpose of increasing the flow capacity of a channel as a means of flood control (Bolton and Shellberg 2001), the disconnection of the floodplain is often perceived as the proper alternative to maintain the safety of life and property. The disconnection of the floodplain results in more isolation of side channels and wetlands (Bolton and Shellberg 2001).

7.4.3.3.5 Groins and Bank Barbs

A primary purpose of groins and bank barbs is to store sediment along the shoreline and prevent shoreline erosion. Groins are common in marine, lacustrine, and riverine environments. They are finger-like, vertical barriers extending from the shore/bank and oriented obliquely to the flow. They are often placed in series. They impede the downdrift/downstream movement of sediment. In rivers, groins and bank barbs are typically constructed in sets along the outside of a meander bend, with the primary function of redirecting flow and bed material away from the bank and toward the middle of the channel. In marine systems, they are constructed to encourage sediment deposition at specific locations. Structures built primarily for other purposes, such as boat ramps and beach access staircases, may also function like a groin (WDFW 2003).

In riverine sytems, flow velocity in a channel is proportional to the hydraulic radius and inversely proportional to roughness (Leopold et al. 1964). Bank barbs are intended to redirect flow toward the center of the channel using weir hydraulics over the structure. In contrast, groins are typically exposed above high water and are designed to divert flow (and bed sediment) around the structure. Both classes of structures reduce near-bank velocities, increase centerline velocities, retard bank erosion, cause local bed scour around the groin tip, and trap fine sediment and debris between structures on the downstream side of the structures (Lagassee et al., 2001; Li et al., 1984). Bed scour into a substrate of mixed particle sizes (i.e., sand and gravel) can selectively remove finer sediment and cause the substrate to coarsen. The depth and extent of bed scour depends on the water depth, approach velocity, and shape and size of the obstruction (Richardson and Davies 2001).

Because the rate and caliber of sediment supplied to a channel can influence the substrate size (Dietrich et al. 1989), changes in sediment supply can alter the composition of substrate used by HCP species. Groins and bank barbs can reduce the supply of suitably sized substrates for spawning fish and invertebrates by limiting natural processes of channel migration and bank erosion. Deposition of the finer sediment downstream can bury organisms and alter substrates.

Groins may interrupt surf-zone generated alongshore currents and circulation. Because groins rarely protrude into depths significantly (more than 10 feet) below mean lower low water (MLLW), they do not play an important role in tidal and estuarine water circulation. However, they may alter the movement and deposition of sediment.

Groins and bank barbs are usually constructed of placed rock or riprap, instead of sheet pilings or other impermeable structures that impede the exchange of hyporheic water. However, if a groin or groin-like structure uses sheet piles or other significant, impermeable, embedded elements (e.g., isolating more than 10 lineal feet along the shoreline from groundwater influence), it may alter hyporheic flow and affect water temperature.

Marine shorelines that have been modified by human activities tend to have less LWD and driftwood than unmodified beaches (Herrera 2005; Higgins et al. 2005). In particular, jetties and groins redistribute LWD such that it concentrates in certain areas and is absent in others (Miller et al. 2001).

7.4.3.3.6 Jetties

Jetties alter both the bathymetry and littoral drift of the area around and under such structures both in exposed (Komar 1998) and sheltered settings (NRC 2007).

Jetties are designed to limit deposition in a navigable channel and to provide wave protection for vessels (Dean and Dalrymple 2002). As a part of jetty installation, substrate can be placed that is completely artificial (Komar 1998).

Jetty installation in rivers is extremely rare because one of the main purposes of a jetty is to obstruct littoral transport, which does not occur on most rivers. In rivers, transport is not confined to the shoreline, and areas near the bank are generally areas of deposition (Chow 1959).

Jetties restrict natural geomorphic processes along the shoreline and often fix the location of estuarine exchange (e.g., at the Columbia River mouth). These geomorphic changes will persist for the design-life of the structure and can impose significant impacts on fish and invertebrates. Jetties may prohibit migration of fish and invertebrate species or life-history stages. The costs of replacing a newly constructed structure may create a strong incentive against the additional investment required to address the problem correctly. This may delay the actions necessary to protect the fish migration corridor, perhaps as long as the design-life of the underperforming structure.

7.4.3.3.6.1 Altered Sediment Supply and Deposition

Jetties are designed to prevent sediment from depositing in a navigational channel. The principal effect of a jetty is to obstruct natural littoral transport, thus starving the downdrift shoreline (Dean and Dalrymple 2002). Jetties have even initiated shoreline instability on adjacent shorelines (Dias and Neal 1992) and redistributed turbidity in their vicinity (Sukhodolov et al. 2004). Alteration of sediment transport patterns can present potential barriers to the natural processes that build spits and beaches and provide substrates required for plant propagation, fish and shellfish settlement and rearing, and forage fish spawning (Haas et al. 2002; Penttila 2000; Thom and Shreffler 1996; Thom et al. 1994). In addition, a considerable amount will often deposit on the updrift side of a jetty. This causes the shoreline to protrude into the water body, distorting sediment transport farther up the shoreline (Komar 1998).

Weir jetties are submerged at most water levels for some portion of their length, usually the landward-most end. These features allow the passage of sediment for localized deposition in some inactive portion of the navigational channel (Seabergh and Kraus 2003). Weir jetties have a tendency to alleviate some of the geomorphic and hydraulic modifications associated with jetties; however, they do initiate change in the substrate and tend to produce geomorphic disturbance (Ranasinghe and Turner 2006).

By examining habitats used by juvenile salmonids, Fresh (2006) concluded that the conversion of sandy, mobile substrates, such as those on natal deltas, would produce a greater impact on salmonid rearing than those on naturally immobile shorelines. Because Puget Sound shorelines are diverse in terms of sediment mobility (Finlayson 2006), the effect on juvenile salmonids from shoreline hardening is highly site specific and could be small in places where the shoreline is naturally immobile. Unfortunately, jetties are often located near river mouths (and deltas) where the transition from mobile, sandy substrate to an immobile, rocky substrate will be most detrimental to juvenile salmonids.

7.4.3.3.6.2 Altered Wave Energy

Jetties are generally constructed out of rock or poured concrete. Therefore, they result in and cause the retention of wave energy in the surrounding area (Komar 1998). In addition, ship traffic associated with the addition of a pair of jetties can interact with these artificial boundaries, causing a significant increase in wave energy in between the two jetties (Melo and Guza 1991). The modified relationship between topography and wave energy caused by a jetty results in a shoreline that is out of equilibrium with natural shoreline processes (Komar 1998). The effects are generally independent of jetty design (i.e., weir jetties are as prone to these effects as exposed jetties), although some best management practices (BMPs) can reduce these effects. Wave energy artificially accumulates in some areas and is diminished in others.

Jetties may decrease complexity of the shoreline by deflecting wave action from the littoral zone. Wave action creates complex littoral habitat by removing fine or silty sediments (Beauchamp et al. 1994). Wave action may also be a source of desirable spawning substrate.

Jetties have been shown to both increase (da Silva and Duck 2001) and decrease (Sherwood et al. 1990) tidal prisms, depending on the characteristics of the tides and freshwater input and the nature and geometry of the alterations.

7.4.3.3.6.3 Altered Groundwater/Surface Water Exchange

Jetties change the shoreline from a dynamic, loose surface to a rigid, immobile one along their length. Although there are distinct differences between artificial substrates used in jetty construction, they all behave over time like bedrock shorelines, similar to extremely coarse-clastic beaches in Puget Sound (Finlayson 2006). The primary difference between these installments is whether they permit the exchange of groundwater with the marine system. In the construction of a jetty, it is common for pilings to be placed near the shoreline to ensure that the landward end of the jetty remains intact. In these cases, groundwater connections with the sea are interrupted. Submarine groundwater discharge has been documented to play an important role in the circulation of fluids and nutrients on many coasts throughout the world (Gallardo and Marui 2006; Johannes 1980; Michael et al. 2005). Solid concrete walls and steel pilings allow no flow-through and likely have additional impact as compared to other artificial substrates (e.g., riprap) (Nakayama et al. 2007). Sheet pilings could interrupt the free exchange of groundwater between the sea and the uplands. If this occurs, deleterious effects on nearshore ecosystems are likely (Nakayama et al. 2007).

Dumped rock or riprap jetties that do not have sheet piles associated with them do not impede or eliminate the exchange of groundwater with supratidal areas. Therefore, these types of jetties or their analogs do not exhibit groundwater impacts.

7.4.3.3.7 Breakwaters

7.4.3.3.7.1 Marine Breakwaters

Breakwaters modify the wave environment in the nearshore. This redistribution of wave energy can have a number of interrelated indirect and direct impacts on fish and invertebrates, and these may be grouped into two categories: those that relate to changes in substrate, and those that change water column characteristics. Reduction in wave energy from natural levels lowers near bed shear stress, resulting in the deposition of finer sediments (Miller et al. 1977).

Breakwaters are generally constructed out of placed rock, parallel to the shoreline, and are specifically designed to reduce wave energy between them and the shoreline (Dean and Dalrymple 2002). Thus, they diminish wave energy shoreward of the structure while wave energy is generally increased offshore (Dean and Dalrymple 2002). The patterns of wave energy produced by emergent and submerged breakwaters are different (Ranasinghe et al. 2006). Breakwaters are often used in series to protect a shoreline from erosion, and sometimes to enhance a beach nourishment project (Dean and Dalrymple 2002). They are typically used on sandy, open coastlines (Dean and Dalrymple 2002), although recent work has shown that they are equally effective at shoreline protection in coarse-clastic environments (King et al. 2000) more typical of Puget Sound (Finlayson 2006).

Breakwaters create a new shoreline that is rigid and immobile along its length. Many different materials have been used to construct breakwaters including riprap, reinforced concrete, pre-formed concrete elements like dolos, and timber structures (NRC 2007). Regardless of the material used, the addition of immobile substrate affects fishes and invertebrates (USFWS 2000). These impacts are generally most pronounced if the structure has a vertical wall, rather than a steep slope (Bulleri and Chapman 2004).

Although breakwaters are designed to protect areas from wave energy and therefore initiate deposition, they have been shown to induce scour on the seaward side of their ends (Sumer et al. 2005). This is primarily associated with artificial rip currents developed in these areas. However, there have been no experimental studies that have documented impacts on forage fish spawning areas.

Breakwaters are not designed to alter nearshore current velocities; however, there is evidence that they can unintentionally cause strong rip currents (Bellotti 2004; Dean and Dalrymple 2002). Also because they function essentially as a new obstacle to flow, they can also reduce velocities in other areas. The relationship between flow velocity and a change in substrate is related to the boundary shear stress (Miller et al. 1977). Substrate and aquatic vegetation are removed if a critical shear stress is exceeded. If the shear stress drops, anomalous deposition can occur.

Breakwaters alter nearshore circulation by modifying the transport processes associated with a variety of wave and wave-breaking mechanisms (Caceres et al. 2005).

Breakwaters have been shown to disrupt the littoral transport of sediments and subsequently cut off downdrift shorelines to a sediment supply (Bowman and Pranzini 2003; Sane et al. 2007; Thomalla and Vincent 2003). Reduction or elimination of the sediment supply can inhibit the proper functioning of spits and beaches and cause the elimination of substrates required for plant propagation, fish and shellfish settlement and rearing, and forage fish spawning (Haas et al. 2002; Parametrix 1996; Penttila 2000; Thom and Shreffler 1996; Thom et al. 1994).

In the construction of a breakwater, it is uncommon for structures (e.g., sheet pilings) to be placed that interrupt groundwater transfer between the sea and the shore. However, if the proposed breakwater has this type of design element, groundwater connections with the sea could be interrupted, and submarine groundwater discharge impacts would result.

7.4.3.3.7.2 Lacustrine Breakwaters

Breakwaters are generally installed on open, exposed coasts (Komar 1998) and are rarely used in lacustrine environments. Most of the work that has been performed on breakwaters in lacustrine environments has been conducted in the Great Lakes (Fitzsimons 1996; Marsden and Chotkowski 2001; Olyphant and Bennett 1994), which are substantially larger (and therefore subject to much larger waves) than any lakes in Washington State. Lakes are subject to long-term water level variability but not to tides. As a result, the size of the breakwater that may be required is significantly smaller and can be placed much closer to shore. This would mean the area of alteration associated with breakwaters would be generally smaller in lakes than in marine waters.

7.4.3.3.7.3 Riverine Breakwaters

Permanent breakwaters are built to protect the shoreline from wave energy (Dean and Dalrymple 2002). Nearly all rivers in Washington State are too small (both in width and depth) and fast moving to have shorelines where waves significantly influence the mobility of the shoreline substrate. Only the Columbia River is generally considered large and deep enough to produce wave heights significantly affecting the substrate and erodibility of its banks. Floating, temporary breakwaters, rather than permanent structures, are used in Washington riverine systems, and would be considered overwater structures .

Generally, water crossings are unlikely to result in significant direct alteration of the hyporheic and groundwater environments because they impact short stream reaches. However, if the water crossing contributes to an indirect effect, e.g., by facilitating land use change or floodplain development, then those indirect impacts could have a more substantial impact.

The principal effects of channel confinement on groundwater and hyporheic function are identified by Bolton and Shelberg (2001). Effects likely to be observed in connection with water crossing structures include:

- Changes in hyporheic chemistry attributable to altered vegetation in the riparian areas (most likely as a result of the impacts of road approaches, which impact a substantially larger area than bridges and culverts *per se*)
- Reduced hyporheic exchange due to increased sedimentation from various causes likely to be a minor effect for most water crossings)
- Lower base flows attributed to reduced recharge from a straightened channel (likely to be a minor effect for water crossings, which straighten short, isolated sections of channel)

7.4.3.4 Culverts

7.4.3.4.1 New Culvert Placement

The improper matching of culverts to local hydraulic and geomorphic conditions can result in a variety of channel responses, some of which create barriers to fish passage (e.g., outfall drops caused by localized scour), and others that modify habitat conditions (e.g., the creation of road-impounded wetlands).

Because the surface of a stream is roughly parallel to its bed (Dunne and Leopold 1978), water surface slope is mainly altered by changes in channel gradient. A culvert or other non-erodible artificial streambed has a fixed gradient, which may or may not be consistent with channel gradient when the culvert is installed and may later be inconsistent if gradient changes due to other factors. Bates (2003) provides extensive discussion of the role of culvert gradient in determining channel response, particularly for steeper channels and retrofit situations where the culvert gradient is steeper than that of the associated channel.

Culverts “lock” a stream channel by fixing it within artificial bounds set by the culvert walls. Closed culverts can lock the channel in the vertical dimension by imposing a fixed base level. This locking prevents the channel from adjusting to flow and sediment supply variability by altering its cross section and gradient; consequently, adjustment occurs by altering channel hydraulics, potentially destabilizing the channel. This effect is most pronounced in the immediate vicinity of the culvert and results in relatively frequent disturbance of in-channel habitat in the affected area.

In freshwater systems, the most common and pervasive substrate modification is the placement of pipe (as opposed to bottomless) culverts. Such culverts may acquire a veneer of bed material but usually are bedded by whatever material the culvert is made from, usually metal, plastic, or concrete. Culverts often have a small diameter compared to the functional channel width upstream and downstream. Culverts, because they closely confine the channel within a pipe, have some specific impacts on channel hydraulics that are most apparent in step-pool, pool-riffle and plane bed channels, where the stream commonly shows a highly variable capacity to transport its sediment load.

The impacts of culverts identified by Bates (2003) include:

- Channel realignment that eliminates natural features such as meanders, spawning riffles, and other diversity in the channel.
- Shortened channels that carry flows at higher velocity, causing streambed instability and downstream scour and bank erosion.
- Sediment mobilization that can smother redds downstream.
- Changes in stream base level that can destabilize the channel and cause reduced hydrology in floodplain water bodies.
- Upstream bed and bank instability if the culvert is undersized, which causes the repeated formation and draining of an upstream backwater pool.
- Blocking the downstream movement of coarse sediment such as boulders and LWD.

- Spawning gravels replaced with culvert pipe.
- Rearing habitat replaced with culvert pipe.
- No streambanks inside the culvert pipe.
- No riparian inputs of leaf litter or terrestrial insects along the culvert pipe.
- No pool, riffle, or hyporheic (in-gravel) habitat within the culvert pipe.
- Few or no benthic invertebrates in the culvert.
- No plants growing on substrate within the culvert, because it's dark.
- Culvert may contribute to loss of off-channel habitat.

When culverts are not designed appropriately for their hydraulic and geomorphic context, the culvert may fail to meet the dual objectives of providing fish passage while adequately conveying flood flows. Culverts that produce high exit velocities may scour the channel at the outlet, leading to an enlarging outfall drop that creates a fish passage barrier over time. Culvert designs that fail to address sediment transport requirements may aggrade over time, creating a barrier condition and reducing the hydraulic capacity of the structure, leading to flooding. Roads have commonly been placed at the edge of river valleys, perpendicular to stream channels draining onto the valley floor. Channels in these settings are naturally depositional, requiring the channel to migrate in response. Culvert designs that fail to recognize these characteristics are likely to aggrade and fail over time.

7.4.3.4.2 Culvert Removal, Retrofitting, and Replacement

Many existing culverts have altered the process of channel migration and evolution, as well as the transport of sediment and woody debris, particularly in cases where barrier conditions are created. Alterations of these physical processes are commonly associated with changes in channel gradient and morphology upstream and downstream of the culvert. Culvert removal or replacement with stream simulation either partially or fully eliminates this restriction, allowing the channel to adjust to a new equilibrium condition. The intent of the stream-simulation approach is to provide a culvert configuration that allows for natural channel processes to operate to the greatest extent possible.

The intent of culvert removal is to restore and reconnect the natural hydraulic and geomorphic processes, reducing or eliminating ecosystem fragmentation. Current culvert replacement guidance favors approaches that at least partially restore these processes (e.g., the stream-simulation and no-slope approaches). These approaches are generally expected to produce a net benefit, particularly when the existing structure is a complete barrier to fish passage. In certain cases, however, removal of the culvert or replacement with a structure that reconnects natural geomorphic processes can lead to broader hydraulic and geomorphic consequences, such as headcut migration or alterations to road-impounded wetlands.

Retrofitting existing culverts is not expected alter existing hydraulic and geomorphic effects in most cases, as this option will maintain the existing structure and not significantly perturb the current channel geometry. However, the placement of internal weirs or baffles can decrease flow capacity, which may impose backwater effects upstream of the structure, leading to potential sediment aggradation, bar formation, and changes to flood elevations. These perturbations can also promote debris accumulation, increasing the risk of structural failure. Depending on the amount of material captured, the natural sediment transport rate, and the maintenance frequency and methods used, this could result in effects on substrate composition in downstream reaches

7.4.3.4.2.1 Headcut Migration

Culvert removal or replacement can reinitiate headcuts that have been arrested by the existing structure, allowing these headcuts to continue to migrate upstream.

Bed scour occurs at culvert outfalls, initially the result of high flow velocities exiting the structure, and then by the impinging jet produced downstream of a sudden drop in channel elevation (Jia et al. 2001). As the water jet penetrates the pool and reaches its bottom, the jet divides into two jets parallel to the bed and in opposite (upstream and downstream) directions (Flores-Cervantes et al. 2006). In homogeneous soils, upstream migration of the scour hole occurs as the upstream jet scours the headcut face, and as the downstream jet removes this sediment and sediment delivered from upstream. Flores-Cervantes et al. (2006) showed that plunge pool erosion varies with the headcut height, flow rate into the pool, and soil properties. The formation of a scour pool at a culvert outfall sets up the condition for headcut or knickpoint propagation upstream if the culvert is removed.

In general, headcut migration will occur when erosion of the headcut face by the upstream jet is faster than the erosion of the bed at the top of the headcut (Flores-Cervantes et al. 2006), and when there is sufficient transport capacity downstream to remove the eroded sediment from the plunge pool (Jia et al. 2001). The distance a headcut propagates upstream will depend on how these conditions change with headcut migration and whether the headcut encounters resistant materials.

Headcuts are most often caused by downstream perturbations and include changes to processes related to hydrology and hydraulics, interruption of sediment transport, hardened bank stabilization or confinement modifications, or the lack of large woody debris that contributes to channel stability. In many cases, arrested headcuts are the cause of outfall drop formation at the mouth of the culvert that leads to a barrier condition. The outfall drop can become quite large in some cases, creating a large change in gradient across the structure. Culvert removal or replacement will likely reinitiate the arrested headcut and cause channel incision, bank instability, and bedload mobility, with a number of detrimental changes in habitat conditions in upstream reaches. Based on experience in Washington State, the potential for headcut migration is a factor that must be considered in 50 percent or more of culvert removal or replacement projects (Bates 2007). While headcut migration can be avoided in many cases by employing appropriate channel modifications, these measures are not always practicable or desirable due to cost, concerns about private property access, and the fact that instream structures interfere with natural geomorphic recovery after the culvert is removed.

Over time, headcut migration would be expected to return the channel gradient and floodplain connectivity to an equilibrium condition, provided that other factors occur (principally, that LWD of sufficient size to trap and retain sediments is available for recruitment).

7.4.3.4.2.2 Channel Incision

Culvert removal or replacement can change channel incision. Channel downcutting associated with headcut migration can cause a range of habitat-related effects.

Channel incision decreases the channel gradient and destabilizes the banks (Kondolf et al. 2002; Sandecki 1989). Bank erosion can increase the local supply of fine sediment and result in channel instability (Sear 1995), leading to increased bedload mobility and ongoing water quality effects in the form of sedimentation.

Lowering of surface water elevations can disconnect side channel and off-channel habitats, as well as reduce the frequency and extent of floodplain inundation. These forms of fragmentation can substantially reduce the extent and productivity of aquatic habitats. Channel incision can result in the loss of floodplain and channel complexity through the fragmentation of off-channel habitats, and can adversely affect riparian vegetation (Castro 2003, Kondolf et al. 2002). Decreased lateral connectivity with side-channel, slough, and floodplain ponds can have a range of effects on HCP species. Side channels create refugia for juvenile fish (Jungwirth et al. 1993), while floodplain ponds and backwater sloughs create zones of high retention and productivity that provide vital rearing habitat (Hall and Wissmar 2004; Sommer et al. 2005) and important sources of organic material for the channel (Tockner et al. 1999). The loss of connectivity between the river and these habitats can result in a decrease in organic matter recruitment (Tockner et al. 1999; Valett et al. 2005) and reduced access to valuable foraging and rearing habitats (Henning et al. 2006).

When channel incision exposes underlying bedrock, it can significantly reduce the productivity and quality of aquatic habitat for a range of fish species, particularly salmonids dependent on alluvial bedded systems for spawning habitat and forage (Kauffman et al. 1993). Depending on the underlying geology, bedrock exposure can accelerate weathering and erosion in lower gradient systems (Stock et al. 2005).

Channel incision can lead to temporary simplification of channel form, creating relatively uniform hydraulic and geomorphic conditions over extended lengths of channel. This reduction in habitat complexity can have a range of adverse effects on HCP species.

7.4.3.4.2.3 Alterations to Road-Impounded Wetlands

Culvert removal or replacement may dewater or otherwise alter road-impounded wetlands, leading to hydraulic and geomorphic changes and potentially a shift to wetland type habitat. Removal or replacement of the culvert can lead to reestablishment of natural geomorphic processes, with a range of effects on instream habitat conditions. The potential dewatering of road-impounded wetlands is a factor for consideration in a relatively low number of cases, estimated to be less than 5 percent of all culvert projects (Bates 2007). The cases where potentially significant hydraulic and geomorphic effects are likely to occur represent a small component of this total (Barnard 2002).

The quality of wetland habitats produced by road-impounded wetlands can vary (Barnard 2002). In most cases, these wetlands are of marginal habitat value, and the importance of restoring natural stream processes is overriding. In rare circumstances, however, high-value habitats may have developed that are occupied by species of interest. In cases where a significant change in hydraulic gradient is induced by the barrier, deposition of fine substrates will occur upstream of the culvert, and the interception of these sediments will cause some degree of sediment coarsening in downstream reaches. Because road-impounded wetlands can raise surface water levels, they may inundate adjacent floodplains more often, creating wetland conditions (Hammerson 1994). Larger impoundments with increased floodplain connectivity are also likely to accumulate organic material, increasing the size of the sediment wedge behind the barrier.

These perturbations and the related ecological stressors they impose range in severity depending on the size of the road-impounded wetland, the volume and characteristics of impounded sediments, and the equilibrium gradient of the restored channel.

7.4.3.5 Fish Passage Structures (Fish Passage Weirs and Roughened Channels)

Fish passage projects can alter flow conditions in the vicinity of the structure by altering channel morphology and hydraulics. Changes in flow velocities may significantly alter sediment transport. The presence of a fish passage structure may accelerate or slow streamflow in different portions of its zone of influence. For example, if a permanent weir installed to prevent upstream dispersal of invasive species creates an impoundment, altered flow velocities in the impoundment will cause increased sediment deposition. In contrast, a structure such as a roughened channel may increase flow velocities in slackwater areas to moderate flows elsewhere. Increased velocities can scour bed material and benthic organisms (Camargo and Voelz 1998).

Depending on configuration, fish passage structures may also change channel geometry. For example, an impoundment formed by a permanent barrier weir may cause upstream channels to widen, and downstream channels will likely become narrower. Because flow velocity in a channel is proportional to the hydraulic radius (the cross-sectional area of the channel divided by the wetted perimeter) and inversely proportional to roughness (Leopold et al. 1964), changes in flow velocity will ultimately change the channel geometry. Altered depth and width downstream of a fish passage structure may disconnect the river from its floodplain and side channel habitats, potentially reducing habitat accessibility.

Flow through fish passage structures will commonly increase local velocities and turbulence downstream of the structures, making fish passage difficult (Baker 2003). While fish passage structures are intended to provide passage benefits, when compared to the natural stream baseline, effects on HCP species may occur. For example, lampreys have been observed migrating over weirs, with short bursts of movement followed by extended resting periods (Quintella et al. 2004). The sea lampreys seemed affected by increasing fatigue, which the authors attributed to initiating a new burst of movement without fully recovering from the previous exertion.

The effects of fish passage structures on sediment composition and stability may range from relatively benign in the case of roughened channels, to more extensive in the case of barrier weirs that create impoundments and interrupt sediment transport.

Permanent fish passage weirs are typically designed to not interrupt the transport of sediment, LWD, and organic material. They are likely to affect reach-level sediment sorting, without necessarily having a broad effect on sediment transport and, by extension, sediment composition.

In some instances, increased velocities associated with weirs can indirectly affect HCP species by causing local bed scour around structures and result in a corresponding deposition of sediment downstream. Bed scour into a substrate of mixed particle sizes (e.g., sand and gravel) can selectively remove finer sediment and cause the substrate to coarsen. Likewise, increased deposition of the finer sediment downstream can bury organisms and result in finer substrate.

7.4.3.6 Bridges

Bridges can fix a stream channel within artificial bounds set by the bridge abutments and approach fills located on the floodplain. This prevents the channel from adjusting to flow and sediment supply variability by altering its cross section and gradient; consequently, adjustment occurs by altering channel hydraulics, potentially destabilizing the channel. This effect is most pronounced in the immediate vicinity of the locking structure and results in relatively frequent disturbance of in-channel habitat in the affected area.

7.4.3.6.1 Altered Wave Energy

Bridges located in the wave zone have the potential to affect wave direction and intensity. The literature on potential impacts is focused on overwater structures such as piers, but the physical processes involved are common to piling- and abutment-supported bridges as well.

7.4.3.6.2 Altered Groundwater/Surface Water Interactions

Generally, bridges are unlikely to result in significant direct alteration of the hyporheic and groundwater environments because they impact short stream reaches. However, if the water crossing contributes to an indirect effect, e.g., by facilitating land use change or floodplain development, then those indirect impacts could have a more substantial impact.

The principal effects of channel confinement on groundwater and hyporheic function are identified by Bolton and Shelberg (2001). Effects likely to be observed in connection with bridges include:

- Changes in hyporheic chemistry attributable to altered vegetation in the riparian areas (most likely as a result of the impacts of road approaches, which impact a substantially larger area than bridges themselves)
- Lower base flows attributed to reduced recharge from a straightened channel (likely to be a minor effect for bridges, which straighten short, isolated sections of channel)

7.4.3.7 Conduits

A pipe or other conduit trenched across the bottom of a stream, although customarily placed below the depth of scour, may function as a gradient control structure if subsequent downcutting occurs. Shallowly buried conduits can impose a fixed vertical base level on a stream channel. This prevents the channel from adjusting to flow and sediment supply variability by altering its gradient; consequently, adjustment occurs by altering channel hydraulics, potentially destabilizing the channel. This effect is most pronounced in the immediate vicinity of the consduit.

7.4.3.8 Dams

The presence of a dam dramatically influences the hydraulic and geomorphic properties of a riverine system. If a dam is located close to coastal and estuarine areas, it may affect the hydraulics of nearshore environments as well. These modifications include altered wave energy, altered current velocities, and altered nearshore circulation.

7.4.3.8.1 Altered Water Flow

Dams tend to reduce peak flows and increase base flows (Magilligan and Nislow 2005), especially for systems where dams are used for hydropower generation. Flow variability is changed from a natural fluctuation to one based on human needs. The changes in flow variability translate into changes in daily high and low water, which can alter flooding and inundation of side channels and floodplains, thereby affecting habitat connectivity.

Dams causes change in channel width and depth. Upstream of a dam, both depth and width increase; downstream, the average depth and width decrease (Tiemann et al. 2004). Because flow velocity in a channel is proportional to the hydraulic radius (the cross-sectional area of the channel divided by the wetted perimeter) and inversely proportional to roughness (Leopold et al. 1964), changes in flow velocity ultimately change the channel geometry. Altered depth and width downstream of a dam disconnect the river from its floodplain and side channel habitats, potentially reducing habitat accessibility and increasing the stranding of aquatic species.

Changes in flow variability can contribute to changes in species composition. High flows, which can displace organisms downstream, help maintain biodiversity through natural flow variability. When stable flows persist in the presence of a dam, organisms adapted to stable flows dominate and diversity will be reduced (Bednarek 2001). Dam removals have been shown to increase species diversity by restoring the natural flow variability. A dam removal on the Chipola River in Florida increased fish diversity downstream from 34 to 61 species (Hill et al. 1993).

Intermittent flooding and draining are needed for the regeneration of riparian forests. In the presence of dams, a loss of flooding reduces forest productivity, suppresses tree growth, and increases tree mortality (Kozlowski 2002). In addition, upstream flooding from reservoir inundation kills trees and seed sources, resulting in inadequate seed supplies for downstream forests (Kozlowski 2002).

Alteration of flow can have impacts far downstream. Reduced freshwater flows can affect tidal mixing and translate into impacts on marine species. Migration patterns, spawning habitat, and species diversity for adult and larval stages of fish and invertebrates are affected by the presence of dams upstream (Drinkwater and Frank 1994). Changes in tidal surges will particularly impact weak swimming fish or early life-history stages that rely on swimming with tidal flows during migration upstream or downstream during spring high flows (Dadswell 1996; Oullet and Dodson 1985).

Inherent in altered flow variability is the change in flow velocities. During times of water release from a dam, velocities downstream can become quite large; however, when water is held back, velocities downstream are depressed.

Flow velocities influence swimming activity and respiration in fish species. High flows below Hells Canyon Dam on the Snake River caused increased swimming activity and subsequently higher O_2 consumption, leading to suppressed movement in white sturgeon (Geist et al. 2005). The study suggested that high flows and velocities, even of short duration, can restrict the movement of juvenile white sturgeon; however, these increases may not cause an increase in energy expenditure due to the adaptation of white sturgeon to high-flow environments. For other HCP species that prefer slower velocities (e.g., Pacific lamprey) high velocities caused by dam releases may be more prohibitive.

Increased flow velocities during water releases can also cause fish species to rest in areas of slower moving water in order to recover from increased activity. This behavior can result in unsuccessful recruitment from delayed migration upstream for anadromous species (e.g., salmonids, sturgeon, lamprey), or increased predation from holding in slow pools downstream of dams and high-velocity reaches.

7.4.3.8.2 Altered Sediment Supply, Transport and Deposition

Changes in flow velocities may also significantly alter sediment transport. The presence of a dam slows river water upstream, causing increased sedimentation in the impoundment behind the dam. Downstream, increased velocities from water releases can scour bed material and benthic organisms (Camargo and Voelz 1998). Altered sediment transport can increase erosion downstream, widen the channel, and reduce channel roughness (Assani and Petit 2004).

Dams modify the sediment available to species for spawning and rearing by blocking the contribution of sediments from upland or upstream source areas.

Several studies have documented how dam-created reservoirs act as sediment sinks (Ahearn et al. 2005; Teodoru and Wehrli 2005). As fine particles settle out above dams, they can fill in cobble and boulder habitat and raise (aggrade) the stream bed (Bednarek 2001). As water velocities slow upstream of dams and as water enters the impounded area, sediment settles out, causing sedimentation upstream of a dam and "clean water," that has little to no suspended sediments downstream (Assani and Petit 2004; Kondolf 1997). Kondolf (1997) describes clean water as sediment starved; there is the potential to scour and erode downstream environments as the stream tries to regain sediment equilibrium. Increased erosion and incision downstream can lower groundwater tables and affect riparian vegetation through reduced access to water (Gillilan and Brown 1997). If erosion is extremely high, incision down to bedrock can occur and effectively reduce hyporheic and groundwater–surface water interactions (Assani and Petit 2004). Increased erosion can cause bank failures, resulting in large sediment inputs and a loss of riparian vegetation (Dietrich et al. 1989; Kondolf 1997; Sear 1995).

The reduction in suspended sediment (and turbidity) directly downstream of a dam can also influence predation of those species waiting to pass over dam structures. Experiments have shown that white sturgeon larvae predation by prickly sculpin increased in the presence of low-turbidity water (Gadomski and Parsley 2005). This suggests that some species use sediment as cover to some extent.

Impacts from altered sediment transport are not limited to the riverine environment; depending on the location of the dam and the river system, impacts on coastal ecosystems are also possible. The reduction of sediment supply to estuarine and coastal environments will change habitat quality and cause erosion of beaches that rely on sediment from rivers. For example, the lack of sediment supply from two large dams on the Elwha River, Washington, has contributed to a loss of beach and coastline habitat (DOI 1995).

Increased velocities associated with dams can indirectly affect HCP species by causing local bed scour around structures and with a corresponding deposition of sediment downstream. Bed scour into a substrate of mixed particle sizes (e.g., sand and gravel) can selectively remove finer sediment and cause the substrate to coarsen. Likewise, deposition of the finer sediment downstream can bury organisms and cause the substrate to become finer.

A high level of substrate fines in channel substrate from a dam may hinder the connection between surface and groundwater, limiting vertical and lateral connectivity between these two habitat types (Edwards 1998; Pusch et al. 1998). This lack of connectivity can degrade conditions for riparian zone vegetation, reducing LWD recruitment to the stream channel and subsequently limiting habitat-forming and maintaining processes. Effects on ecological functions and freshwater aquatic species associated with degraded connectivity between different riverine habitat elements are well documented (Bilby and Bisson 1998; Hershey and Lamberti 1992; Karr 1991; Kelsey and West 1998; Montgomery et al. 1999; Naiman et al. 1992; Reiman and McIntyre 1993; Stanford and Ward 1992; Stanford et al. 1996).

7.4.3.8.3 Dam removal

Dam removal alters sediment transport in a river. Because sediment is trapped upstream of a dam, removal of the dam will increase sediment downstream. Although the potential for increased suspended sediment downstream from dam removal is highly likely, the effects are often short term. The impact depends on the type of removal, time of the year, length of time the dam was present, flow rates, and flow velocities (Bednarek 2001). Studies have shown that sediment pulses from dam removal can migrate through a system in days to weeks to years (Bednarek 2001); in some cases, sediment releases are similar to a periodic storm event (Winter 1990). Dam removal is one possibility for restoring natural sediment transport in a riverine system.

Doyle et al. (2002) and Doyle et al. (2003) demonstrated that channel evolution after small dam removal follows the classic model of incision and widening that is induced by base-level lowering. Accumulated sediments erode rapidly and are transported to lower gradient, downstream reaches where aggradation is likely to occur. Water depths and flow conditions within the former impoundment will change, and the wetted perimeter will decrease. Bank stability within the former impoundment declines until the channel adjusts and vegetation becomes established (Bednarek 2001; Doyle et al. 2002, 2003; Pollock et al. 2003). Bank failure induces channel-widening and bed-aggradation processes that lead to an eventual dynamic equilibrium in the longitudinal profile of the channel (Schumm et al. 1984).

Downstream channel geometry will be only temporarily affected by the removal of small impoundments (Pollock et al. 2004). Deposited sediment will be transported to downstream low-energy environments (e.g., pools, channel margins) but will likely be entrained and exported farther downstream in subsequent flooding events. Upstream channel geometry will change more dramatically. The main channel in the upstream reach responds by narrowing. Channel narrowing may limit access to shallow water habitat and decrease the surface area exposed to solar radiation (Margolis, Raesly et al. 2001).

A study of the effects of removal of two small dams in Wisconsin found insignificant sediment export, attributed to the small impoundment size and relatively high thalweg velocities that limited sediment accumulation prior to removal (Orr et al. 2006).

7.4.3.8.4 Effects of dams on invertebrates

Altered flow variability can dewater floodplain habitat and strand fish and invertebrate species. As an example of effects on invertebrates, a drawdown of the Lower Granite

Reservoir on the lower Snake River killed many California floaters, western floaters, and western ridged mussels. Freshwater mussels are known to migrate to avoid receding waters and can be vulnerable to predators during this time. If dewatering occurs for long time periods, mussels may bury themselves during dewatering, but there is a risk of mortality if waters do not return to normal levels before the mussels overheat (Nedeau et al. 2005).

In a survey of native freshwater mussels in the United States and Canada, Williams et al. (1993) concluded that declines in populations were caused by habitat destruction, dams, siltation, and channel modifications Watters (1999) summarized the effects of impoundments on mussel species in the United States, and deposition of silt within and downstream of impoundments has been linked to extinction of several mussel species nationwide.

7.4.3.9 Weirs

The hydraulic and geomorphic impacts of weirs on HCP species are similar to those of dams. Flow over weirs increases turbulence below structures and increases local velocities, making fish passage difficult (Baker 2003). Sea lampreys have been observed migrating over weirs with short bursts of movement following by extended resting periods (Quintella et al. 2004). The sea lampreys seemed affected by increasing fatigue, which the authors attributed to initiating a new burst of movement without fully recovering from the previous efforts.

Weirs drop channel elevation, which can alter channel slopes. Abrupt changes in slope can alter sediment transport and represent migration barriers for fish. In a study of fall heights from weirs on movements with the common bully (*Gobiomorphus cotidianus*) and adult and juvenile inanga (*Galaxias maculatus*), Baker (2003) showed that both species were restricted by falls of 0.4 inches (10 cm), and the passage of adult inanga was restricted by falls of 0.8 inches (20 cm). Atlantic salmon in the Pau River (France) were able to pass over weirs of 59.1 inches (1.5 m) in height but had difficulty passing weirs of 98.4 inches (2.5 m) in height (Chanseau et al. 1999).

7.4.3.10 Outfalls

The hydraulic and geomorphic impacts of outfalls are diverse. Outfall design and effluent characteristics play an important role in the degree of impact on fish and invertebrates. Well-designed outfalls that discharge small flow rates of effluent with similar constituents (i.e., temperature, salinity, turbidity and density) as the receiving water do not have significant hydraulic and geomorphic impacts.

7.4.3.10.1 Submerged Outfalls

Given the sensitive nature of the sediment supply along the shorelines of Puget Sound, structures that span the beach foreshore, which is the zone of maximum sediment transport, may have significant effects (Finlayson 2006). Outfalls that are submerged below the water surface, but elevated above the natural grade, have the potential to act as groins, interrupting the natural flow of sediment along the shoreline (Herrera 2006b). If submerged outfall plumbing protrudes above grade and above the closure depth[2], such an interruption of longshore transport has the potential to be significant. If the outfall protrudes above grade but below closure depth, the effects will be minimal.

Hydraulic impacts of submerged outfalls are related primarily to the flow rate and the physical and chemical properties of the effluent. Typically, submerged outfall outlets are located below the closure depth and below significant light penetration, such that aquatic vegetation and fish use are limited. In these situations, hydraulic modifications likely have a minimal effect on fish and invertebrates. However, if the effluent is of a different density than the ambient water, stratification of the basin can occur, which can have severe water quality impacts, most notably through eutrophication and benthic anoxia (Fischer et al. 1979).

To prevent the deposition of debris in the outfall and the diffuser ports, minimum velocities are often required (Fischer et al. 1979). Large velocities can alter nearshore circulation patterns by mixing otherwise distinct water masses, even if outfalls are sited in deep waters (Fischer et al. 1979). Scour can also occur as a result of large discharge velocities (Rice and Kadavy 1994).

If the outfall outlet is located above the closure depth, significant impacts on local geomorphology can occur, including changing substrate, changing nearshore circulation patterns, and possibly excluding fish from key habitats with high velocities. High velocities (or changes in nearshore circulation produced by them) could also remove aquatic vegetation. Because many of the HCP species use surface waters preferentially to deeper water, the impact on fish and invertebrates would be greater the shallower the outfall outlet. The precise distribution of velocities and their change from preconstruction conditions would need to be determined with a hydraulic numerical model.

If outfalls or outfall pipes protrude above grade, alterations in local wave energy can occur. As hard points along the shoreline, outfall structures can result in the retention of wave energy in the surrounding area (Komar 1998). Regardless of the nature of the alterations, the modified relationship between topography and wave energy results in a shoreline that is out of equilibrium with natural shoreline processes (Komar 1998). As a result, wave energy artificially accumulates in some areas and is diminished in others. This redistribution of wave energy can have a number of interrelated indirect and direct effects on fish and invertebrates, including changes in substrate and changes in water column characteristics.

[2] Closure depth is "the depth beyond which no significant longshore or cross-shore transports take place due to littoral transport processes. The closure depth can thus be defined as the depth at the seaward boundary of the littoral zone." (Mangor, Karsten. 2004. "Shoreline Management Guidelines". DHI Water and Environment, 294pp.)

7.4.3.10.2 Exposed Outfalls

Outfalls can alter the composition of bed and bank materials by virtue of adding material coarser than the ambient bed or by adding flow and coarsening the existing sediments. If the outfall extends into the channel, it can deflect high-velocity flows to the center of the channel and induce flow separation. Outfalls can also initiate the deposition of fine sediments leeward of the protruding structure. Protruding outfalls can reduce the local supply of coarse sediment by deflecting bed sediment from the riverbank to the center of the channel. Because the rate and caliber of sediment supplied to a channel can influence the substrate size (Dietrich et al. 1989), changes in sediment supply can alter the composition of substrate used by HCP species.

The most important hydraulic and geomorphic effect associated with exposed outfalls is the ability for the outfall to create a scour pool at its outlet. Increased velocities associated with flow constrictions created by protruding outfalls can indirectly affect HCP species by causing local bed scour around structures and corresponding sediment deposition downstream (Richardson and Davis 2001). In addition, high-velocity effluent can initiate bed scour, causing the selective removal of finer sediment, coarsening the substrate. Likewise, deposition of the finer materials originating from the outfall downstream can bury organisms and cause the substrate to become finer.

Often in the outfall design, riprap or other immobile surfaces are added to prevent erosion at the outlet. This protective material often protrudes into the channel, floodplain, or sea floor. These modifications potentially have a significant impact on the substrate surrounding the outfall outlet. They can:

- reduce hydraulic roughness,
- increase velocity and bed scour,
- reduce the supply of suitably sized substrates for spawning fish and invertebrates by limiting natural processes of channel migration and bank erosion.

Exposed outfalls can protrude into a stream or river channel and intercept the flow of sediment downstream. In this case, the outfall behaves like a groin and can disrupt the substrate. Protruding, exposed outfalls can alter the velocity field in riverine environments by redirecting flow away from the banks and toward the center of the channel, just as groins can do (Lagasse et al. 2001). The formation of flow-separation eddies adjacent to these structures results in areas of relatively low velocity in these areas and along the protected bank (Lagasse et al. 2001). The net effect is to confine the flow, contributing to increased velocity and bed scour. If outfalls do not protrude and their effluent exits at a small velocity, their impact on the flow regime is negligible.

Placement of outfalls above grade eliminates the potential to maintain riparian vegetation. This can increase the flow velocity and increase the potential for scour and substrate coarsening through a reduction in hydraulic roughness compared to vegetated conditions (Millar and Quick 1998).

Most outfalls do not require the use of sheet pilings or other impermeable structures that impede the exchange of hyporheic water with main river channels. However, if an outfall is placed parallel to a river or stream channel and it is sufficiently large, the outfall pipe itself has the potential to disrupt or eliminate hyporheic exchange, reduce lateral habitat connectivity, and alter stream temperatures buffered by groundwater inputs.

7.4.3.11 Intakes and Diversions

Intakes and diversions may involve a number of hydraulic and geomorphic modifications. As with outfalls, the design of pipes or diversion channels transporting water into upland infrastructure can interfere with the transport of sediment, if those pipes are exposed above grade. Typically, this results in coarsening and erosion of the substrate in the lee of the pipe, as well as deposition and fining on the upstream or updrift side of the pipe. These impacts can usually be avoided by constructing the pipe below grade.

Other hydraulic and geomorphic modifications are related to altered flow regimes and changes in channel geometry. Diversions reduce flows downstream, which can lead to habitat loss (Kingsford 2000) and changes in channel width, depth, and velocity (Dewson et al. 2007).

Unique to intake structures, inflowing water can attract fish toward the intake structure. All intakes should be screened in some manner to exclude fish. Unscreened intakes represent a severe hazard to all fish and their larvae; entrainment by an unscreened intake can cause mortality to all life stages of fish that inhabit areas near intakes (Newbold and Iovanna 2007). The area of influence of an intake is highly site- and design-dependent (Edinger and Kolluru 2000). To identify the area of influence of the intake, flow near any proposed unscreened intake should be investigated with a suitable hydraulic model.

The primary effect on invertebrates is through displacement of natural substrates. The emplacement of hard surfaces, either from the intake itself or piping connecting it to upland infrastructure, presents a surface on which invasive species can colonize. In the Great Lakes, extensive colonization by zebra mussels has completely clogged intake pipes (Ram et al. 1992).

7.4.3.12 Tide Gates

Tide gates regulate movement of water, sediments, and organic material between river–floodplain and marine–estuarine wetland environments. The presence of tide gates impacts hydraulic and geomorphic processes in a number of ways. Tide gates alter tidal exchange by preventing free movement of saline and fresh waters in estuarine settings. Channel geometry can be changed through restriction of freshwater flow through the tide gate. Substrate composition can be altered through changes in flow regime, similar to changes imposed by dams. The duration of inundation and water depths above tide gates do not resemble natural conditions. The hydraulic and geomorphic modifications that occur will likely adversely affect HCP species.

Hydraulic impacts extend both upstream and downstream from a tide gate, potentially affecting a range of habitats. Flow rates and flow paths are altered in the presence of a tide gate (Vandenavyle and Maynard 1994). Tide gates alter natural tidal flushing by restricting tidal flows for an unnaturally long time. In some cases, tide gates can be closed for more than 50 percent of the day (Giannico and Souder 2005).

Tide gates may alter channel geometry in several ways. When tide gates are open, high velocities through the tide gate may increase scour downstream, creating a scour pool (Giannico and Souder 2005; Zhang et al. 2000). These increased velocities are a function of the upstream–downstream differences in hydraulic head. Scour can alter the depth and width of the channel and marsh and potentially lead to habitat loss and fragmentation, as well as a loss of desirable depths if scour pools become large.

When the tide gate is closed, water velocity upstream of the gate slows, upstream water begins to pool, increasing the channel width and depth. Sedimentation increases landward of the structure due to slower velocities. The lack of two-way tidal flushing in the presence of tide gates also increases sedimentation (Anisfeld et al. 1999). Sedimentation can gradually convert aquatic habitats to terrestrial habitats as distributary channels and other features fill with sediment.

7.4.3.13 Beaver Dams

Beaver impoundments can increase vertical connectivity in riverine environments. Vertical connectivity, as defined by Ward (1989), is a measure of the exchange between groundwater and surface water through the bed and banks of the channel (i.e., hyporheic exchange). It has recently been quantitatively shown that beaver dam presence can raise local groundwater tables and thereby promote hyporheic exchange with the channel (Westbrook et al. 2006).

By creating a head differential across the structure of the dam, beaver activity directs water into the benthos. These waters either move through interflow or shallow groundwater routes to the floodplain and channel below the dam. This vertical connectivity between surface and groundwaters is associated with a number of important ecological processes, including the biogeochemical processing of nutrients and pollutants, and the creation of zones of upwelling that are preferential spawning habitats for salmonids and other species. In a study of small man-made dams in the black Prairie region of Texas it was found that the result of upstream impoundment was to increase riparian vegetation production by increasing hyporheic exchange through the riparian corridor (Duke et al. 2007). In a separate study in the Rocky Mountains, researchers showed that beaver dams and ponds increased water retention during flooding events and attenuated the wet season flows. Instead of efficient routing through the channel which was observed below the impoundments, in areas affected by beaver the flow routing was more complex and the local groundwater level was elevated during both low and high flows (Westbrook et al. 2006).

Increased hyporheic exchange can be beneficial to salmonids because the eggs of these species require well oxygenated gravels for proper egg development (Ecology 2002; Groot and Margolis 1991), and hyporheic exchange promotes increased oxygen levels in the benthos (Greig et al. 2007). Additionally, increased hyporheic exchange has been associated with nutrient uptake (Sheibley et al. 2003) and may attenuate the transport of dissolved and particulate metals (Gandy et al. 2007).

There is little if any experimental research on the impact of beaver dam removal on aquatic species. Instead, the impact must be inferred from studies which have assessed the benefits of beaver impoundments and other studies that have addressed the ramifications of small man-made dam removals. The removal of beaver dams can impact the HCP species which utilize beaver pond habitat during their life history.