7.3 Ecosystem Fragmentation

Ecosystem fragmentation refers to the disruption of ecological processes by reducing the connectivity between different components of the ecosystem. The mechanism of ecosystem fragmentation differs from other mechanisms because it combines the elements of physical features, time, and location to represent how potentially covered species would be impacted by loss of ability to access these features.

HPA-permitted structures can be categorized as contributing to ecosystem fragmentation by:

- Altering habitat complexity
- Altering migration patterns/ presenting barriers to fish passage and dispersal
- Altering lateral connections between rivers and floodplains

7.3.1 Altered Habitat Complexity

7.3.1.1 General Alterations: All Environments

Human modifications of the environment, including activities permitted through the HPA program, can simplify and fragment habitat. Loss of habitat complexity can contribute directly to decreased growth, survival, and population productivity of HCP species. Studies have indicated that decreased habitat complexity negatively affects the survival and growth of aquatic organisms. Reduced shelter availability will increase predation and is not energetically favorable for fishes.

- In a recent study by Finstad et al. (2007), it was found that juvenile Atlantic salmon exhibit accelerated mass loss rates with decreasing access to shelter, indicating that the juvenile fish had to expend greater energy when there was no available shelter.

- In another study by Babbitt and Tanner (1998), tadpole survival was 32 percent greater under high than under low cover, suggesting that increased cover decreased predator foraging efficiency. Although the prey in this study were not HCP species, the effect of cover on predation rates can be extrapolated to HCP species that utilize vegetated cover during early lifestages.

- Limited habitat availability may lead to density-dependent mortality for those species that cannot find unoccupied cover and may be exposed to increased predation or high-energy environments (Forrester and Steele 2004).

7.3.1.2 Ecosystem-Specific Effects: Marine and Estuarine

Lagoons, sometimes called pocket estuaries, provide important rearing habitat for juvenile salmonids, including Chinook (Busby and Barnhart 1995) and coho (Minakawa and Kraft 2005) as well as Pacific herring (Saiki and Martin 2001). Access to high-quality lagoon habitat has been shown to be the critical path in the restoration of Chinook in the Skagit River system (Beamer et al. 2005).

Lagoons have declined both in terms of size and number due to human modifications to lowland coastal areas in Puget Sound (Beamer et al. 2005). Lagoons can be lost due to changes in the tidal prism (Sherwood et al. 1990). The primary impact of a loss of lagoon habitat would be to expose juvenile salmonids and forage fish to increased risk of predation (Hood 2006; Wagner and Austin 1999).

Shallow water marginal habitats in the nearshore environment are similarly important to a variety of salmon species (Fresh 2006). Loss or fragmentation of these habitats can have significant effects on the survival, growth, and fitness of dependent species.

The loss of shallow water and lagoon habitats can affect invertebrate species. The Olympia oyster uses lagoons, therefore the species could be susceptible to losses due to changes in tidal prism (Baker 1995).

7.3.1.3 Ecosystem-Specific Effects: Riverine

An indirect impact from the loss of decreased habitat complexity is an increase in nutrient loading to downstream receiving waters. Channel complexity promotes the retention of water and organic material.

Ecological connectivity is essential between riverine and riparian ecosystems (Stanford and Ward 1993).

Side channel habitat provides low energy refugia for fishes and is largely viewed as a net benefit to stream organisms (Jungwirth et al. 1993). Rock weirs create low velocity zones in the lee of the structures and accelerate flow between the rocks. These variable habitats are utilized by different species during various lifestages. For instance, juvenile Chinook salmon have been shown to take refuge in low velocity habitat behind rock weirs, while steelhead parr utilize deep water habitat between the rocks during summer low flow periods (Fuller 1990).

Ecosystem fragmentation can lead to changes in genetic diversity. A study of the genetic variation within European grayling populations from the Skjern River (Denmark) showed that present-day grayling differed from historic stocks due to the drift of larvae downstream and restricted migration upstream (Meldgaard et al. 2003).

Fishes' requirements for structural diversity and complexity within habitats may differ by life stage. Li et al. (1984) documented lower larval and juvenile fish densities and richness along revetted versus natural shorelines in the Willamette River, but higher adult abundances. Species captured by Li et al. (1984) included Chinook salmon, speckled dace (*Rhinichthys osculus*), torrent sculpin (*Cottus rhotheus*), and largemouth bass (*Micropterus salmoides*).

7.3.1.4 Ecosystem-Specific Effects: Lacustrine

Diversity and the interconnectedness of different shoreline types have been found to be more crucial than any particular substrate or vegetation type on lake shorelines for a variety of species (Pratt and Smokorowski 2003). This may explain the dramatic differences observed in ecosystem health when modified and unmodified shorelines are compared (Roth et al. 2007; Scheuerell and Schindler 2004).

Altering the wave energy reaching the shoreline can lead to a loss or fragmentation of existing spawning habitat for sockeye salmon. Sockeye salmon are the primary HCP species potentially affected by lakeshore modifications. Lake shorelines represent crucial spawning habitat for sockeye (Burgner 1991; Scheuerell and Schindler 2004). Juvenile Chinook salmon also use lacustrine littoral zones (Sergeant and Beauchamp 2006). Sergeant and Beauchamp (2006) have shown that although substrate preferences for juvenile Chinook are weak, they prefer fine substrates with cover.

No studies showing a relationship between effects on invertebrates and loss of nearshore habitat in lacustrine ecosystems were found.

7.3.2 Altered Migration Patterns/ Barriers to Fish Passage and Dispersal

7.3.2.1 General Effects: All Environments

Access to habitat is one of the ecological functions that is important to potentially covered species and that may be impaired to some degree by HPA-permitted structures.

Any structure that unintentionally selects against population diversity is likely to be detrimental to its long-term viability (McElhany et al. 2000; Thompson 1991).

7.3.2.2 Ecosystem-Specific Effects: Marine and Estuarine

Loss of access to estuarine and floodplain rearing habitats has been broadly implicated as a contributing factor in the decline of anadromous salmonids in the Pacific Northwest, particularly those species with demonstrated dependence on these habitat types (such as coho, Chinook, and chum salmon) (Beechie et al. 1994; Giannico and Souder 2004; Gregory and Bisson 1997). Loss of access to floodplain and estuarine rearing affects growth and fitness and, in the case of estuarine rearing, limits the potential residence time in brackish water habitats that facilitate the physiological transition from fresh to marine water during smoltification. These factors can influence survival.

7.3.2.3 Ecosystem-Specific Effects: Riverine

Alteration of longitudinal connectivity and resulting changes to both upstream and downstream habitat complexity will impact HCP species because many of the HCP fish species require a range of habitat types throughout their life histories. Potentially covered species must be able to access habitats with velocities favorable to their physiological needs as a species or a life stage. For example, such species as mountain sucker and lamprey require slow water as a general habitat need, while juvenile salmonids require slow-moving water for cover and energy refuge. Many species find the quiescent habitats they need in off-mainstem channels, backwaters, tidal sloughs, and shallow water areas.

Most fish must be able to move freely upstream and downstream during both juvenile and adult stages (Sargeant et al. 2004). Adult salmon returning to their spawning streams must have unobstructed upstream migration corridors. Specific studies include:

- Juvenile salmon rearing in rivers have been found to move both upstream and downstream to utilize rearing habitat, even in streams where spawning has not been documented (Kahler and Quinn 1998).

- Steelhead trout were found to use main channel and side tributaries equally (Bramblett et al. 2002), and coho salmon were observed more often in tributaries (Bramblett et al. 2002).

- Radio-tagged Pacific lamprey in the John Day River (Oregon) were observed using the lateral margins of riffles and glides, and used boulders for cover (Robinson and Bayer 2005).

- In Montana, mountain suckers were shown to prefer riffles (Wydoski and Wydoski 2002).

Little is known about the effects of longitudinal connectivity on invertebrate species. However, freshwater mussel larvae rely on attachment to host fish (Nedeau et al. 2005), so reduction in fish populations may have an indirect effect on mussels such as the California floater and western ridged mussel. In fact, several studies summarized by Watters (1999) showed that the loss of fish hosts has been linked to the decline of native mussel species.

Loss of habitat access may also restrict the dispersal of HCP freshwater invertebrate species. This can occur in two ways. First, the structure may restrict the distribution of host fish, affecting the dispersal of parasitic larvae (Vaughan 2002; Watters 1996). Second, the structure may restrict upstream movement of mussels and snails capable of crawling along the stream bottom (Vaughan 2002).

The potentially covered freshwater mussels migrate through their range as larvae attached to fish gill membranes (Brim Box et al. 2004), and loss of habitat access for the host fish would also lead to a reduction of the mussels' range. Among the 35 fish that Brim Box et al. (2004) found to be carrying mussel larvae, 34 were speckled dace and one was redside shiner (*Richardsonius balteatus*). Brim Box et al. (2004) found no mussel larvae attached to the small numbers of smallmouth bass, northern pikeminnow (*Pyctocheilus oregonensis*), and largescale sucker (*Catostomus macrocheilus*) that they inspected. Species such as California floater mussels may face demographic risks from the unintentional limitation of fish passage because the full range of their host fish species is poorly understood, meaning that the migration behavior and swimming requirements of these species may not be well accounted for. Likely host-fish species include native minnows (cyprinids) and non-native mosquito fish (Nedeau et al. 2005).

7.3.3 Altered upstream transport of organic material

Alteration of fish migration patterns can lead to the alteration of upstream transport of organic material, particularly marine-derived nutrients associated with the carcasses of anadromous fish species. Numerous studies have documented the contribution of marine-derived nutrients provided by anadromous fish on food web productivity (Brock et al. 2007; Chaloner et al. 2007; Chaloner et al. 2002; Chaloner and Wipfli 2002; Gross et al. 1998; Hicks et al. 2005; Lessard and Merritt 2006; MacAvoy et al. 2000; Merz and Moyle 2006; Minakawa et al. 2002; Mitchell and Lamberti 2005; Moore et al. 2007; Nagasaka et al. 2006; Scheuerell et al. 2005; Schindler et al. 2005; Yanai and Kochi 2005; Zhang et al. 2003). Reductions in the delivery of marine-derived nutrients can affect food web productivity in ways that are detrimental to the growth, fitness, and productivity of juvenile salmonids as well as other native fish species (Bilby et al. 1998; Heintz et al. 2004; MacAvoy et al. 2000).

Marine-derived nutrients distribute broadly in aquatic ecosystems (Cederholm et al. 1989), demonstrably affecting algal growth and nutrient export (Brock et al. 2007; Chaloner et al. 2007; Chaloner et al. 2002; Mitchell and Lamberti 2005; Moore et al. 2007; Schindler et al. 2005; Yanai and Kochi 2005). Several studies have examined the influence of marine-derived nutrients on the productivity of riparian vegetation, which in turn affects habitat structure (Bartz and Naiman 2005; Ben-David et al. 1998; Helfield and Naiman 2001, 2002; Merz and Moyle 2006; Nagasaka et al. 2006; Naiman et al. 2002; Scheuerell et al. 2005).

Structures that improve passage of native fish species will likely produce beneficial effects on food web productivity and habitat structure, with attendant benefits on HCP species dependent on these habitats. Conversely, reduction in upstream transport of allochthonous nutrients will detrimentally affect the productivity of native fish populations. This inference is supported by research documenting the uptake of marine-derived nutrients by juvenile salmonids and other native fish species (Bilby et al. 1998; Heintz et al. 2004; MacAvoy et al. 2000).

While no data were identified regarding the direct influence of marine-derived nutrients on HCP invertebrate species, changes in ecosystem productivity resulting from decreased fish passage could affect the growth and fitness of these species, through changes to the forage base for filter feeding and grazing invertebrate species. Because the availability of marine-derived nutrients affects the productivity of host fish populations (Bilby et al. 1998), the dispersal of freshwater mussels, which are dependent on fish to transport their parasitic larvae upstream against the current, will be reduced where fish productivity has been adversely affected.

7.3.4 Altered connections between channels and floodplains

Potentially covered species require habitats that offer varying depths, velocities, and cover for refuge from their predators and from needlessly expending energy. Floodplain habitats provide these diverse habitat conditions. A reduction in the amount of side channel and floodplain can impact species that rely on any floodplain-associated habitats such as wetlands, beaver ponds, bogs, and off-channels.

Floodplains are habitat-rich areas with pools and side channels that are important nurseries for aquatic organisms (Bednarek 2001). Oxbow lakes are important habitat for juvenile fish (Penczak et al. 2003). Floodplains require periodic inundation. Even low-occurrence flooding (e.g., a 2-year flood) is important to sustain floodplain habitat diversity and to support aquatic species (Thoms 2003). The loss of LWD may also contribute to floodplain-channel connectivity losses. Floodplain–channel connection augments allochthonous carbon budgets in restored channels and engages habitat that would otherwise be inaccessible.

Riparian wetlands provide food resources for adjacent, less productive aquatic ecosystems and function as habitat for fish and invertebrates. Shallow flooded riparian areas are some of the most productive habitat within a watershed (Bunn et al. 2003; Junk et al. 1989; Schemel et al. 2004; Sommer et al. 2005; Sommer et al. 2001). Consequently, access to and resource transport through this zone is essential for the healthy functioning of river-floodplain systems. Research has indicated that riparian wetlands are nutrient sinks and carbon sources for adjacent channels (Tockner et al. 1999; Valett et al. 2005). In this fashion, wetlands function as zones of transformation, converting inorganic nutrients to organic forms which can be consumed and transferred up the food chain. Organic material is exported from the floodplain in four primary forms, coarse woody debris, coarse particulate organic matter, dissolved organic matter, and suspended algal biomass. Suspended algal biomass represents one of the most important forms of carbon export from floodplains because of the high nutrient content of the algal cells (Muller-Solger et al. 2002). Studies have indicated that when hydraulic residence time on floodplains is in the range of 2 days (Ahearn et al. 2006), algal biomass concentrations may begin to increase, reaching a maximum level at approximately 10 days (Hein et al. 2004). Although site specific, these studies indicate that riparian wetlands with extended hydraulic residence times will produce high levels of algal biomass. This algal biomass is an important food resource for organisms in both the wetland itself and the connected channel or open water habitat.

Studies summarizing the use of floodplains and riparian wetlands by fish and shellfish include:

- Floodplain connectivity creates forage and refuge habitat for several species of fish (Feyrer et al. 2006; Henning 2004).

- Chinook that rear on floodplains have been shown to grow faster than those rearing in adjacent channels (Sommer et al. 2001).

- Hayman et al. (1996) found sub-yearling Chinook in higher densities at backwater and off-channel habitat than in mainstem edge habitat of the Skagit River. This use of habitat implies that access to all stream reaches, even those absent of adult salmon, is needed by juvenile salmon.

- In a 2004 study of the Sacramento splittail (Ribeiro et al. 2004), fishes rearing in floodplain habitat were healthier and larger than fish from the same cohort that did not rear in this type of environment.

- Floodplain areas are important rearing habitats for coho (Beechie et al. 1994; Swales and Levings 1989). Juvenile coho have also been shown to use floodplain habitats when they are available, even in locations where they have disconnected in the past (Henning et al. 2006; Morley et al. 2005).

- Swales and Levings (1989) found that off-channel habitat in the Coldwater River, British Columbia were vital rearing areas for coho, while juvenile Chinook, steelhead, and Dolly Varden were most abundant in floodplain ponds.

- In a survey of habitat use in Southeast Alaska, Dolly Varden were observed using step-pools (Bryant et al. 2007) and were more common in tributaries compared to the main channel (Bramblett et al. 2002).

- Steelhead use both main channel and side channel habitat (Bramblett et al. 2002).

- Egg dispersal into newly inundated habitat has been hypothesized to increase the number of Columbia River white sturgeon. Larval white sturgeon have been shown to disperse to flooded riparian habitats for early rearing. Fragmentation of these habitats may be a factor in the decreased productivity of this species (Coutant 2004).

- Green sturgeon tagged on the Rogue River (Oregon) showed use of off-channel coves (Erickson et al. 2002).

- Side channels create refugia for juvenile fish (Jungwirth et al. 1993).

- Off-channel areas offer spawning habitat for sockeye salmon (Hall and Wissmar 2004).

- 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).

- Floodplain ponds and backwater sloughs also contain important sources of organic material for the channel (Tockner et al. 1999). The loss of connectivity between the channel and these habitats can result in a decrease in organic matter recruitment (Tockner et al. 1999; Valett et al. 2005).

- Whether for rearing or spawning, the viability of wetland habitats hinges upon connectivity with the adjacent open water system. Too much connectivity, and productivity of the wetland decreases (Tockner et al. 1999). Too little connectivity and the stranding of organisms may become a problem (Henning et al. 2006; Sommer et al. 2005).

- Loss of connectivity can reduce access to valuable foraging and rearing habitat (Henning et al. 2006).

- It has been estimated that in the Skagit Valley, 41 percent of sloughs and 31 percent of small tributary habitat has been lost to channelization for agricultural purposes (Beechie et al. 1994).

- Where the interaction of LWD with the channel is affected by channel incision, the ability of debris jams to promote access to floodplain habitats may be diminished.

While these potential effects are of concern, care should be taken not to assume that they are universal in extent or severity. In many instances, it may be appropriate to allow a stream system to return to a natural equilibrium gradient through channel incision. For example, many culverts occur in smaller stream systems with naturally limited floodplains and off-channel habitat. Regrading this type of channel and placing grade control structures will produce extensive short-term adverse effects on aquatic habitat conditions and HCP species occurring in these environments. These effects may significantly outweigh those that result from allowing a natural channel response to proceed, while the intermediate- to long-term benefits of both approaches are comparable. In such cases, the cost and the short-term effects of channel regrading would not be justified, unless property or infrastructure faces unacceptable risk. Given these complexities, it is desirable to include a licensed geologist and a qualified aquatic biologist in the design process to avoid unnecessary actions and/or undesirable outcomes.

7.3.5 Activity-Specific Effects

7.3.5.1 Jetties

A number of processes associated with the installation of a jetty could lead to a loss or fragmentation of existing habitat. The construction and maintenance of a jetty can limit the accessibility of fish through changes in both the structure of the shoreline and its characteristics (linear and impermeable versus undulating and covered in large woody debris). This can take the form of complete removal of habitats, such as the elimination of lagoon habitats due to changes in alongshore sediment transport patterns or the tidal prism. However, habitat accessibility can also be compromised if characteristics, such as having different hypsometry (distribution of depths) or elimination of riparian vegetation and large woody debris, make the shoreline inhospitable to the HCP species.

These include a loss of accessibility to coastal lagoons through a reduction of the tidal prism, a loss of substrate and appropriate depth necessary for spawning, and a change in the abundance of predators and prey.

Jetties and other hard shoreline structures have the potential to both attract and deter use of the nearshore by fish, birds, and people. Jetties have been shown to be a locus for shorebird activity, mostly as a result of jetties acting as concentrating mechanisms for passively drifting horseshoe crab eggs (Botton et al. 1994). Shorebirds are similarly attracted to Pacific herring spawn in natural settings on the western shore of British Columbia (Rodway et al. 2003). The concentrations of spawn and shorebirds, however, were associated with hard-substrate outcrops, similar to artificial hard points commonly associated with jetties. Although these concentrations can occur in the absence of man-made structures, the unnatural concentration of spawn on jetties would artificially enhance these processes. The degree to which the concentration of spawn and shorebirds affects the mortality of spawn and the dwindling numbers of Pacific herring or other planktonic breeders is unknown (Rodway et al. 2003). The complex interaction between people, birds, and fish can lead to a net loss of HCP species (Roby et al. 2002).

Jetties have been shown to concentrate juvenile Chinook salmon in some areas due to strong changes in salinity (Yates 2001). Similar features (groins) have been shown to concentrate chum and coho salmon (Miller et al. 2001), while protruding shoreline structures (i.e., analogous to jetties) have been shown to concentrate juvenile salmonids and all of the HCP forage fish species (Toft et al. 2007). These concentrations likely do not reflect an increase in production of these fishes, but rather a concentration due to bottlenecks in access to nearshore habitat. Because these concentration mechanisms are exploited by commercial fishermen (Creque et al. 2006; Miller et al. 2001), the risk of increased catch due to jetty installation likely has a negative effect on salmonid survival and navigation near such activities.

Jetties may pose lingering ecological effects when they are not designed properly to account for movement of sediment and wood alongshore. In the construction and maintenance of jetties, LWD is often removed from the surrounding jetty site and nearby adjacent navigation channels. In addition, altered wave energy and nearshore circulation can cause a change in the transport energy such that less wrack accumulates on beaches adjacent to the jetty.

7.3.5.2 Breakwaters

Breakwaters have not been shown to disconnect nearshore habitats, alter tidal prisms, or significantly influence nearshore stratification in the same way that jetties do. Therefore, breakwaters do not present the same degree of risk of disconnection to crucial habitats (e.g., lagoons) as jetties. The interaction between fishes near man-made structures is more complex than in natural settings and has only been studied in relation to low-crested structures (i.e., breakwaters) and artificial reefs.

As offshore hard structures, breakwaters do, however, have a significant impact on the types of ecologic assemblages found in their vicinity (Perez-Ruzafa et al. 2006). They also have a tendency to increase the numbers of piscivores, which, depending on the species of predator and prey could have a negative effect on HCP species (Pondella et al. 2002). As a result, breakwaters could alter predator–prey abundance and compromise certain habitats for HCP species.

Breakwaters and other artificial reefs have been examined in terms of their productivity for Washington fishes and invertebrates (Buckley and Hueckel 1985). When properly designed, submerged breakwaters generally increase the numbers of fish, including rockfish and lingcod (West et al. 1994). However, there is significant debate in the scientific community as to whether they increase the total productivity of the nearshore or simply attract those species from surrounding waters [i.e., “attraction versus production” (Pickering and Whitmarsh 1997)].

In some locales, submerged breakwaters have been seen as an ecological loss because the goals of constructing a breakwater are different from those of an artificial reef (Bulleri and Chapman 2004). This is particularly true if those breakwaters are fished or if the species of concern are eaten by the fishes attracted to the reef (Pondella et al. 2002). Because the literature is somewhat contradictory, it is important to understand the three factors that have emerged as crucial variables in the determination of the ecological success of a breakwater:

- *Species and diet of attracted fishes*. If the species attracted to and potentially enhanced by the breakwater structures are HCP species [e.g., bocaccio rockfish (Love et al. 2006)], the installation could be considered to have a net ecological benefit. It is also possible, however, that the introduction of predatory fishes could shift biomass away from smaller fishes (Pondella et al. 2002). If these smaller fishes are HCP species (e.g., Pacific herring), the project could present a net loss.

- *Commercial fishing*. If fishing is allowed on the breakwater, the concentration of HCP species can result in a loss in the number of total fish, while protection from fishing has the potential to increase the total number (Guidetti, Verginella et al. 2005).

- *Geometric complexity of structure*. If the structure is simple (with vertical walls), attraction of fish will be restricted and possibly limiting (Bulleri and Chapman 2004; West et al. 1994). However, if the breakwater provides sheltering sites, its installation may be of net ecological benefit [particularly for rockfishes (Love and York 2006)].

Substantial work has demonstrated that, at least for rockfishes, submerged emplacements of rock and other hard substrate can be used as a habitat enhancement measure (West et al. 1994). Although artificial reefs designed for habitat are usually placed in deeper water, several studies have shown that rock placed in shallower waters, typical of submerged breakwaters (Dean and Dalrymple 2002), can have the same benefits (Pondella and Stephens 1994).

Breakwaters change the distribution of wave energy, substrate, and wrack material along the shoreline. Large wood will most likely preferentially accumulate in the lee of breakwaters, similar to the substrate changes induced by these structures (Bowman and Pranzini 2003; Thomalla and Vincent 2003). This would cause the shoreline to be discontinuously covered by LWD, potentially compromising natural migration corridors to HCP fish species that use littoral zones.

Breakwaters restrict deposition and erosion in specific geometries useful for human activities. However, this shoreline geomorphology can be poorly suited for any or all life stages of fish and invertebrates. Breakwaters may pose lingering ecological effects when they are not designed properly to account for channel movement or to allow sediment and wood transport. Breakwaters may interfere with littoral migration of fish and invertebrate species or life-history stages. In such instances, 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 provide appropriate migration for fish, perhaps as long as the design-life of the underperforming structure.

7.3.5.2.1 Breakwaters 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.

The primary differences between breakwaters in lacustrine environments and those in marine environments are the following:

- *Short-term stable water levels*. Lakes, although subject to long-term water level variability, are not generally subject 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.

- *Species of interest*. Although some species use both lacustrine and marine shorelines (e.g., salmonids), most fish and invertebrates use only one or the other, with the freshwater-only species having limited scientific study. Further, because studies of the specific impacts on invertebrates in lakes has been extremely limited, there is a data gap in terms of understanding the specific effects of breakwaters on those freshwater species.

- *Invasive species*. Freshwater breakwaters have been shown to harbor invasive species infestations capable of the wholesale disruption of lacustrine nearshore ecosystems (Marsden and Chotkowski 2001). In particular, zebra mussels present an ongoing and serious threat to Washington freshwaters (WDFW 2004).

7.3.5.3 Groins and Bank Barbs

By forcing flow into narrow corridors, groins can interrupt floodplain-channel connection and thereby cause the loss of habitat area and productivity.

Groins simplify stream structure and focus flow energy into limited areas, causing LWD to be flushed downstream.

Certain types of shoreline protection measures, like groins and bank barbs, may pose lingering ecological effects when they are not designed properly to account for channel movement or to allow sediment and wood transport. Groins and bank barbs may not provide adequate passage for all fish and invertebrate species or life-history stages. In such instances, 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 provide appropriate fish passage, perhaps as long as the design-life of the underperforming structure.

7.3.5.4 Bank Protection and Stabilization

Bank protection can restrict natural geomorphic processes along the marine and riverine shorelines and can impose significant impacts on fish and invertebrates. By altering flow patterns, bank protection can interrupt floodplain-channel connection and thereby cause the loss of habitat area and productivity. Aquatic species must be able to access habitat with water depths favorable to their habitat needs. When favorable depths are lost, species are cut off from habitats they require. Isolation of species from shallow-water habitats can occur when armoring is placed waterward of the OHWL or into the intertidal zone of marine habitats, and the area immediately adjacent to the structure exists at a deeper point than nearshore species can inhabit, forage, or find refuge. The deep water condition can be exacerbated if armoring further causes scour of the bank, erosion of sediment, and lowering of shore elevation.

When bank protection degrades and reduces access to off channel refugia, such as off-mainstem channels, backwaters, tidal sloughs, and shallow water habitats (Beamer et al. 2005), species can either be displaced or be unable to seek refuge and must expend excess energy to maintain position and avoid being flushed out of preferred habitats. Bank protection structures that alter the flow regime, and thus depth and velocity, can impact fish habitat accessibility where water velocity exceeds their swimming ability or creates areas without adequate water depth or sufficient refuge areas.

Bank protection structures that alter depths and velocities in the marine intertidal zone can limit habitat access for prey of potentially covered species; in particular, forage fish such as surf smelt and sand lance spawn on fine-grained substrate in the upper intertidal zone, which may be locally reduced along armored shorelines. Further, Pacific herring spawn on submerged eelgrass and macroalgae in shallow-water areas that may also be reduced along armored shorelines (Thom and Shreffler 1994). Although erosion associated with hardening of the shoreline is often ephemeral, when the sediment supply is not maintained (Finlayson 2006), it presents the possibility of the elimination of elevations necessary for the proper wave and sediment transport conditions for the survival of surf smelt and sand lance larvae, concomitant with a loss of appropriate spawning substrate. When a shoreline is hardened, erosion down to an underlying coarse cobble lag (i.e., a deposit of coarse cobbles [1–5 inches in diameter] left over from erosion in the geologic past) is possible (Finlayson 2006; Herrera 2005). The result is a nearly vertical shoreline at the location of the hardened structure, often colocated with or near the ordinary high water mark (OHWM).

Several studies have looked at the way fish interact with armored shorelines:

- Heiser and Finn (1970) found that juvenile salmonids avoided deep-water areas along bulkheaded shorelines.
- In marine areas, altered water depths along the marine shallow-water migration corridor preclude their use by migrating juvenile salmon (Thom and Shreffler 1994).
- 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.
- Jennings et al. (1999) found that even within armoring types, those that provided higher structural diversity exhibited higher species richness.
- Many freshwater studies have documented that fish species richness and abundance are negatively correlated with bulkheads in general (see review by Kahler et al. 2000).
- Lange (1999) found that the presence of bank bulkheads was negatively correlated to fish abundance and species richness in Lake Simcoe, Ontario.
- Juvenile fall Chinook in the Columbia and Snake rivers were found to avoid riprap shorelines (Key et al. 1994; Garland and Tiffan 1999).

Newcomb's littorine snail requires a narrow band of nearshore intertidal habitat that contains certain marsh plant species (pickleweed, *Salicornia virginica*; Larsen et al. 1995), and inadequate water depth or velocity conditions caused by bank armoring that threaten this plant would also impact the snail. Other potentially covered invertebrates are typically found in deeper-water areas (snails) or in mudflat habitats (oysters), where access to habitat would not be limited by bank protection structures.

7.3.5.5 Dams

Dams affect HCP species through

- Altered longitudinal connectivity

- Altered river-floodplain interactions
- Altered groundwater-surface water interactions
- Altered community composition.

Upstream–downstream connectivity is the most obvious alteration, with a reduction in sediment and food resources, increased potential for predation, and altered temperatures. Because flow variations are dampened by dams, connectivity of the river with its floodplain is reduced. This can result in reduced nutrient cycling, loss of favorable habitat, increased predation, and altered temperatures. Altered hyporheic exchange has similar effects with changes in temperature, nutrient cycling, and loss of refugia for invertebrates. Furthermore, these alterations to ecosystems contribute to changes in species interactions and diversity.

7.3.5.5.1 Altered Longitudinal Connectivity

Dams block the migration of aquatic species, which is one of their most detrimental impacts on riverine ecosystems. Longitudinal connectivity is vital to ecosystem health, as organisms rely on up–down transport in riverine systems in search of optimal conditions for feeding, cover from predators, spawning, and food resources. Depending on the size of the dam, upstream migrations of fish can be completely blocked. In other cases, fish passage structures may allow some individuals to migrate upstream. Although fish passage facilities are constructed at some dams to allow longitudinal migration, delays in passage are common. Indirect effects include increased exposure to predation.

Studies documenting the effects of dams on fish and shellfish populations include:

- Studies have shown that Atlantic salmon (Chanseau et al. 1999) and shrimp (Greathouse et al. 2006) have difficulties migrating over dams and weirs.
- In the Fox River, Illinois, freshwater mussel distribution was limited upstream of a dam site (Tiemann et al. 2007).
- In the Pacific Northwest, salmon, sturgeon, bull trout, and lamprey populations have suffered declines from decreased migration in the presence of dams (Hicks et al. 1991; Jager 2006; Moser et al. 2002; Neraas and Spruell 2001).
- Cumulative effects of dams have been documented as well. In the Columbia River, only 3 percent of tagged Pacific lampreys were able to reach the upper part of the river after passing over three dams (Moser et al. 2002). With each dam passed, the number of successful individuals decreased. In addition, lamprey were observed attempting passage multiple times (Moser et al. 2002).
- Migration delays can result in increased risk of predation or poaching while fish wait for an opportunity to pass a given structure (Bednarek 2001).

- Some fish undergo physiological changes if spawning migrations are delayed. American shad have been known to reabsorb their gonads when returning to the ocean, without releasing eggs and sperm (Dadswell 1996).

- Anadromous salmonids, which begin to decline physically upon entry to fresh water, may experience decreased spawning fitness as a result of delayed passage, including potential mortality before spawning is completed (Caudill et al. 2007).

- Delayed migration of adult Chinook on the Columbia River has been documented at the Bonneville Dam since the 1950s (Schoning and Johnson 1956).

- Juvenile migration downstream can be delayed as free-flowing reaches are transformed into slow-moving/slackwater reservoirs (Peven 1987).

- Caudill et al. (2007) examined the relationship between delayed migration, survival, and spawning productivity by using radiotelemetry to track the behavior and fate of Chinook salmon and steelhead navigating fish passage structures on Columbia River dams. Statistically correcting for other sources of mortality, they found a distinct inverse relationship between the time required for individual fish to transit fish ladders bypassing Columbia and Snake River dams, and survival to reach spawning grounds. While the drivers of this inverse relationship are complex, energy expenditure and stress associated with navigating the structures are primary contributing factors. In combination with other stressors imposed by fish passage structures (e.g., prolonged exposure to elevated water temperatures, increased harvest, and predation pressure), the effects of migration delay induced by fish passage structures appear to be cumulatively significant (Caudill et al. 2007).

- Upstream of a dam, habitat structure is altered from a free-flowing (lotic) habitat to a lake-like (lentic) habitat. In this case, lake-adapted organisms dominate and, in some cases, encourage salmon predation (Wik 1995).

- Downstream of a dam, habitat types (e.g., pools, riffles) can be altered as a result of the effects of changes in flow regime, sediment transport, and substrate composition on channel. After several decades of sediment trapping, the Warche River in Belgium showed significant losses of pool and riffle habitat downstream of a dam (Assani and Petit 2004).

- The effects of restricted access caused by dams and weirs have been broadly implicated in population declines of freshwater fish species from around the world (Northcote 1998).

In addition to their direct effects on fish and shellfish, dams alter LWD dynamics by physically blocking the downstream transport of LWD. Dams reduce LWD inputs through changes in river–floodplain connectivity.

7.3.5.5.2 Altered River–Floodplain Connectivity

Dams (as well as diversions) reduce the occurrence of inundation flows and can alter floodplain ecology, contributing to mortality and poor health of aquatic organisms (Kingsford 2000).

7.3.5.5.3 Altered Community Composition

Dams can result in alterations to natural species composition and diversity.

- Species composition can be altered in the presence of dams as invasive species become more dominant than native species as a result of dramatic changes in the riverine ecosystem (Moyle 1976).
- The losses of native fauna as a result of dams can dramatically alter basal food resources and assemblages of invertebrate competitors and prey (Greathouse et al. 2006).
- Changes in temperature associated with dam impoundments can cause shifts from resident cool water species to warm water species.
- For mussel species, it has been shown that changes in temperature and increased siltation from dams have reduced the number of native species and increased the number of invasive species nationwide (Watters 1999).
- In Japan, Katano et al. (2006) showed that the number of species, total diversity, and biomass of fish were lower above three small-scale dams (4.9–12.8 ft [1.5–3.9 m] in height) compared to downstream reaches. Food webs above dams were simpler relative to downstream communities.
- In New Zealand, species richness of different fish and crayfish were lower in areas upstream of dams (Joy and Death 2001).
- Food web structure and functional feeding groups of macroinvertebrates were changed above and below dams on the Grande River, Argentina (Vallania and Corigliano 2007). The authors found that collector-filterers, scrapers, and predators increased downstream, whereas the collector-gatherers and shredders decreased relative to upstream reaches. A similar result was observed in a series of mountain streams in Spain (Camargo et al. 2005).
- Alterations to species composition and diversity from dams are not limited to freshwater environments. The lack of freshwater inputs from reduced flow regimes can affect species in estuarine and marine environments as well (Drinkwater and Frank 1994).
- On the Olympic Peninsula, the presence of dams on the Elwha River has reduced sediment transport to coastal environments, causing a shift to invasive kelp and

barnacles in the receiving water body (DOI 1995). This reduction of sediment contributed to a loss of estuaries that serve as nurseries for fish and shrimp because sediment bars separating brackish water from the ocean are no longer present (DOI 1995).

7.3.5.6 Dikes and levees

The main ecological connection altered in the presence of a dike or levee is the river–floodplain connection. In addition to floodplain habitat loss, changes in hydrology and geomorphology caused by dikes and levees could potentially lead to an increase in the invasion of exotic species. However, little information is available on this topic and represents a potential data gap.

- After construction of a dike or levee, floodplain, lagoon, and tidal marsh habitats are lost (Hood 2004).

- After dikes were removed on the Salmon River (Oregon), juvenile fall Chinook salmon were observed using many regions of the restored tidal marsh (Bottom et al. 2005).

- A loss of floodplain habitat in China from the construction of dikes and levees resulted in a 74 percent reduction in habitat and caused declines in many types of plant species (Liu et al. 2004).

7.3.5.7 Dredging

In marine and estuarine environments, dredging operations can limit the access of fish through changes in both the structure and characteristics of shorelines (e.g., linear and barren versus undulating and covered in large woody debris). This can take the form of complete removal of habitats, such as the elimination of marine lagoon habitats due to changes in alongshore sediment transport patterns or the tidal prism.

In riverine environments, dredging reduces structural complexity, and alters channel and floodplain form. Dredging can change how water, organisms, food resources, sediments and LWD are transported or retained. Dredging in rivers to improve navigation, and in smaller channels to increase conveyance, lowers the bed elevation. Dredging therefore has the potential to decrease lateral connectivity with side-channel, slough, and floodplain ponds, leading to habitat loss and fragmentation.

In lacustrine environments, dredging can alter the wave energy reaching the shoreline and thereby alter the local recruitment and transport of sedimen, fragmenting the nearshore ecosystem. Juvenile Chinook salmon use lacustrine littoral zones (Sergeant and Beauchamp 2006). Sergeant and Beauchamp (2006) have shown that although substrate preferences for juvenile Chinook are weak, they prefer fine substrates with cover. Because the wave energy caused by bathymetric changes due to dredging could change the local shoreline substrate, it possibly also changes both the distribution and continuity of spawning and rearing areas, increasing the potential for predation.

7.3.5.8 Gravel mining and scalping

Gravel mining can cause channel incision by the removal of gravel from the sediment budget and from the incorporation of excavation pits into the channel. Hydromodifications of riverine environments by gravel mining could result in a loss or fragmentation of existing habitat through alterations in the longitudinal connectivity and river-floodplain connectivity. Pit capture[1] can also result in the fragmentation and loss of spawning and rearing habitats (Norman et al. 1998). Levees constructed to isolate pits from the active channel reduce habitat complexity and dynamic channel migration.

Captured pits become lakes within the river and transform lotic environments into lentic environments. The incorporation of off-channel pits by river capture exposes juvenile salmonids to heavy predation by exotic, warm-water fish. For example, McMichael et al. (1999) showed that predation on juvenile salmonids by predaceous warm-water fishes in the Lower Yakima River is substantial. Smallmouth bass were estimated to consume about 0.5 million salmon smolts per year, resulting in an annual loss of about 1,350 adult salmon.

7.3.5.9 Sediment Capping

Sediment capping projects can limit fish movement and accessibility to various habitats through changes in both the structure of the shoreline and its characteristics. If a Confined Aquatic Disposal (CAD) cell is used, food web alterations may be induced by the attraction of piscivorous fish to the hard habitat of the CAD structure. Sediment capping may also result in alteration of nearshore circulation patterns.

7.3.5.10 Beach Nourishment

The ability of beach nourishment to reconnect or disconnect pre-existing shoreline communities depends on the nature of the shoreline adjacent to the site. If the substrate is significantly different than the shoreline adjacent to it, or if added sediment buries aquatic vegetation, the activity may fragment the alongshore transit of HCP species (Beamer et al. 2005). This is why some researchers have recommended that the substrate used in beach nourishment activities be as close to the adjacent shorelines as possible (Speybroeck et al. 2006). Conflicting recommendations calling for the installation of a coarser substrate have been based primarily on engineering grounds (NRC 2007).

It has been well documented that beach nourishment projects can negatively impact the prevalence of invertebrates on the shoreline (Peterson et al. 2006; Peterson et al. 2000; Rakocinski et al. 1996). Furthermore, it has been shown that these reductions can also impact invertebrate predators (Peterson et al. 2006). However, invertebrate communities respond quickly to disturbance and may, in certain situations, rebound quickly from these impacts (Dernie et al. 2002). The impact of these disruptions of food sources on HCP fish is currently a data gap.

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[1] National Marine Fisheries Service (NMFS) National Gravel Extraction Guidance (05-06-27) defines “pit capture” as “active channel migration into floodplain (gravel) pits.”

7.3.5.11 Reef Creation, Restoration or Enhancement

It is clear that more fish and invertebrates are present at reefs than in open water (Pickering and Whitmarsh 1997). The physical presence of a solid surface enables a greater diversity of organisms to grow and be protected. However, a remaining question from the hundreds of studies of artificial reefs around the world is whether reefs produce more biomass than would exist without the reef or whether they simply concentrate the existing biomass (Pickering and Whitmarsh 1997). In other words, do reefs produce or attract targeted species? Regardless of whether absolute production has increased, it has been suggested that artificial reefs can harbor significant fractions of total fish populations, particularly where natural environments have been declining (Love et al. 2006).

Rockfish are opportunistic piscivores (Yang et al. 2006). Although there have been no studies documenting rockfish preying on juvenile salmon, it is certainly possible given an increase in rockfish numbers near shore. Predation on salmonids by rockfish is currently a data gap and should be considered when siting an artificial reef in marine waters.

As newly available habitat, reefs have a tendency to attract invasive species. Similar hard structures have been the site of invasive communities, both in fresh water and salt water (Marsden and Chotkowski 2001; Wasson et al. 2005). The threat appears to be somewhat correlated to the degree of human alteration of the ecosystem (Wasson et al. 2005). This implies that estuaries and lakes are more prone to invasive species than exposed marine settings. In the case of freshwater invaders, there are species that can disrupt if not eliminate resident fish populations (Marsden and Chotkowski 2001).

Artificial reefs have the capability to connect existing rocky habitats, leveraging the gain from their installation (Thompson et al. 2002).

7.3.5.12 Channel Creation and Alignment

Channel creation and alignment can change how water, organisms, and food resources are transferred through the mosaic of habitat patches that constitute the river-floodplain system. Channel creation and alignment may alter longitudinal connectivity, alter river-floodplain connectivity, and alter hyporheic flow and exchange.

7.3.5.13 Roughened channels

In general, roughened channel projects fall into two categories: reconfiguration of an existing channel or side-channel to provide fish passage, or the creation of an entirely new channel through adjacent uplands or floodplain.

Roughened channels are intended to improve fish passage by promoting connectivity of habitats along the river. However, roughened channels that were improperly designed for their ecologic or geomorphic context, or because of decreased passage performance over time, may result in ecosystem fragmentation through the following mechanisms:

- Roughened channels may impose intentional or unintentional passage barriers, or passability may decrease over time due to design failure or improper maintenance.

- Effects on fish passage may in turn alter the upstream transport of nutrients from distant sources, particularly marine-derived nutrients, affecting ecosystem productivity.

- Unintentional loss of flow can cause organic material to accumulate in the channel bed, only to be released in a large pulse when flow is restored.

- Undersized roughened channels may flood lands never flooded in the past and produce large quantities of fine-grained sediment.

Many studies have identified fish passage structures that fail to provide adequate fish passage for the species they are intended to benefit, or that unintentionally limit passage of nontarget species (Agostinho et al. 2007; Boggs et al. 2004; Bunt et al. 1999; Caudill et al. 2007; Moser et al. 2000; Moser et al. 2002; Naughton et al. 2007)

7.3.5.14 Tide gates

Tide gates may cause ecosystem fragmentation from a loss of longitudinal connectivity. This alteration, combined with altered flow velocities when the gate is open, can block the migration of fishes and invertebrates (Giannico and Souder 2005). Blue crab showed increased difficulty navigating high flows through a tide gate in North Carolina (Rulifson and Wall 2006). Two factors may influence the extent that a tide gate blocks fish passage: the length of time the gate is open, and how wide it opens.

Tide gates may:

- cause a reduction in channel–floodplain connectivity as a result of altered channel geometry and flow regime,

- cause a loss of lagoon habitat,

- alter wave energy, current velocities, and nearshore circulation.

- alter species composition and diversity. For example, Danish wetlands subjected to the influence of tide gates experienced declines in bird species diversity, declines in benthivore abundance, and increases in herbivore abundance (Holm and Clausen 2006). In addition, macrophyte biomass increased, but sea grass diversity decreased. The authors attributed many of these changes in plant communities to altered salinity levels.

- contribute to the loss of large woody debris. Little information is available on LWD dynamics as they are affected by tide gates and represents a potential data gap.

- Gated culverts (tide gates) are also known to restrict fish passage to lateral riverine and estuarine habitats, even when designed according to current engineering standards (Novak and Goodell 2006). Gated culverts that are designed or retrofitted to promote fish passage (e.g., self-regulating tide gates) are likely to cause at least some degree of barrier condition (Novak and Goodell 2006). Because this type of culvert is typically found in estuarine environments, gated culverts have the potential to affect HCP species that use estuarine floodplain habitats, such as juvenile anadromous salmonids.

The degree of these impacts would depend on the volume of the tide gate discharge, magnitude of tidal changes, and local mixing.

7.3.5.15 Fish Passage Structures – General

All fish passage structures, with the exception of culvert removal, have some potential to impose barriers to fish passage when compared to the aquatic ecosystem in its natural condition (i.e., before the presence of man-made passage barriers). Providing passage for all HCP species during all pertinent life-history stages is a guiding principle governing the design of fish passage structures, and it is a difficult challenge.

Fish passage structures may provide less effective passage over time depending on how appropriate the design is for its ecological context and how frequently the structure is maintained.

Upstream migration and other movements within freshwater rearing habitats are important factors to consider when designing structures that will allow fish passage. In comparison to the natural stream baseline, fish passage projects may lead to detrimental effects on native fish populations by affecting their ability to migrate between important habitats. Juvenile salmonids are seasonally migratory, moving between refuge and rearing habitats (Bolton et al. 2002; Kahler and Quinn 1998; Kahler et al. 2001). Juveniles may cover considerable distances to occupy available rearing habitats, indicating that this dispersal mechanism is important to survival (Bolton et al. 2002). Even in the absence of well-defined migratory behavior, the ability to move between different habitat types is nonetheless important for many resident fish species (Rodriguez 2002). The ecological implications of decreased habitat access are potentially significant. Fish passage structures that unintentionally block access to summer and winter rearing habitats may be key factors limiting juvenile survival, growth, and fitness.

Even when a passage barrier project is intended to protect native fish populations, it could have detrimental effects. For example, projects that prevent brook trout invasions of headwater stream populations may unintentionally fragment genetic exchange between resident and adfluvial populations of bull trout. Maintaining this type of genetic exchange within bull trout metapopulations is considered essential for the long-term conservation of the species (Reiman and McIntyre 1993).

Fish passage structures can affect passage success based on life-history stage (i.e., by size). As juvenile salmonids migrate downstream on many larger river systems, they must travel past large dams where they are susceptible to injury and mortality if forced to travel through power turbines. Many experimental fish passage structures have been employed to direct downstream migrations through less injurious pathways, with varying degrees of success.

The interplay between fish swimming performance and hydraulic conditions in fish passage structures becomes increasingly complex with smaller target species. In their review of multiple sources of research on juvenile salmon passage, Kahler and Quinn (1998) noted that numerous *in situ* observations have demonstrated that extrapolation of adult salmon swimming performance curves to juveniles underpredicted the ability of smaller fish to navigate velocity barriers in fish passage structures. Based on postulations in the sources they reviewed, they concluded that complex hydraulic conditions within fish passage structures created low-velocity zones used by juvenile fish to transit the structures. Research conducted by WDFW supports this hypothesis. Kahler and Quinn (1998) suggested that design guidance for velocity limits based purely on swimming performance and mean channel hydraulics is likely to be conservative. However, there are many other uncertainties in the design guidance that are not compensated for by these unintentionally conservative assumptions.

Most regional studies on fish passage performance have focused on larger juvenile salmon (e.g., in the 4–5 inch [100–125 millimeter] range), which may not be fully representative of the requirements of smaller juveniles. While the preponderance of research on swimming performance suggests that ability is essentially constant relative to size across the majority of fish species (Katopodis 1992), this relationship may break down when the complexities of low-velocity pathways and individual adaptive ability are considered.

Fish passage structures may unintentionally select for fish of different size classes or run timing. For example, a culvert that is retrofitted for fish passage may provide adequate passage to salmonids during moderate streamflow conditions, but may be impassable during average high and low flows. In effect, the barrier may unintentionally select against individuals with run timing in the late summer low-flow period and during late fall when streamflows increase to high levels, truncating the genetic diversity of the stock. Similarly, a passage structure may prove impassable to fish above or below a certain size, selecting for smaller or larger individuals. Of particular concern, it is increasingly clear that juvenile salmonids are migratory when quite small and that design criteria in existing regulations may not adequately protect juveniles of smaller size. For example, the Washington Administrative Code (WAC 220-110-070) limits the vertical jumps formed by water-crossing structures to no more than 0.8 feet (9.6 inches) to provide for juvenile fish passage. However, research on juvenile salmonid jumping ability indicates that a vertical drop of this size would effectively limit passage of juvenile salmonids 3 inches in length or smaller. Pearson et al. (2005) found that the proportion of juvenile salmon able to navigate vertical jumps decreased steadily as jump height exceeded 2.5 times body length, with effectively no fish able to navigate jumps in excess of three times body length. However, a number of complicating factors must also be considered, such as weir crest shape, ambient approach velocity, shape of the nappe[2], and downstream approach conditions that can affect this threshold limit.

The ability of fish species to navigate fish passage structures may be over- or underestimated if their swimming and jumping abilities are not appropriately considered.

- In a study of the effects of weir vertical drop heights on the migration behavior of two native diadromous fish species in New Zealand, the common bully and the inanga, Baker (2003) found that juvenile inaga and all life-history stages of common bully were unable to navigate vertical drops of 4 inches (10 cm), and drops of 8 inches (20 cm) were barriers to adult inaga.

- Vertical drops of 12 cm have also been shown to limit passage of juvenile salmonids (Pearson et al. 2005).

- Adult Atlantic salmon in the Pau River (France) were able to pass over weirs between 59.1 inches (1.5 m) and 98.4 inches (2.5 m) in height (Chanseau et al. 1999), drop heights that would completely block passage for many fish species.

Fish passage barriers have been shown to differentially affect passage by sex. Brown et al. (2002) studied migratory Chinook salmon passage of natural waterfalls and found that males were more successful than females at navigating energetically demanding barriers. Man-made fish passage barriers and their remedies could conceivably have similar effects. Alteration of male to female sex ratios can have significant demographic consequences, potentially affecting the viability of the affected population (McElhany et al. 2000; Thompson 1991). However, differential male to female dispersal around barriers may be an evolved strategy to avoid inbreeding and genetic introgression in salmonids (Hutchings and Gerber 2002). This suggests that sexual selection effects should not be assumed without population and site-specific research.

Improperly conceived or maintained fish passage structures may delay migration and/or may be physically taxing to navigate. In the case of adult salmonids, the cost of delayed migration and energy expenditure can have a demonstrable effect on survival, as well as spawning productivity. Caudill et al. (2007) examined the relationship between delayed migration, survival, and spawning productivity by using radiotelemetry to track the behavior and fate of Chinook salmon and steelhead navigating fish passage structures. Statistically correcting for other sources of mortality, they found a distinct inverse relationship between the time required for individual fish to transit fish ladders bypassing

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[2] Nappe – n. A sheet of water flowing over a dam or similar structure. From http://www.answers.com/topic/nappe. Also a geological formation, a section of a cone (in mathematics), and a French culinary term for lightly coating food in a sauce.

Columbia and Snake River dams, and survival to reach spawning grounds. While the drivers of this inverse relationship are complex, energy expenditure and stress associated with navigating the structures are primary contributing factors. (However, extant natural barriers eliminated by impoundments are also energetically demanding (Brown et al. 2002)). In combination with other stressors imposed by fish passage structures (e.g., prolonged exposure to elevated water temperatures, increased harvest, and predation pressure), the effects of migration delay induced by fish passage structures appear to be cumulatively significant (Caudill et al. 2007).

Fish passage structures that primarily consider the passage of one species or class of species (e.g., culvert retrofits designed to pass salmonids) may unintentionally limit the passage of other important species. Species selection can alter species composition and community relationships upstream of the passage barrier, with important implications for conservation of individual species and biodiversity (Agostinho et al. 2007).

There are several examples of species-specific selectivity in the available literature.

- In the Columbia River system, fish ladders designed primarily to provide salmonid passage around mainstem dams perform relatively poorly for passage of Pacific lamprey (Moser et al. 2002). Loss of habitat access is a key factor implicated in the decline of native Pacific and river lamprey populations in the Pacific Northwest.

- Sturgeon passage may be enhanced by the inclusion of rapid velocity segments in fishways and other passage structures (Cheong et al. 2006; Webber et al. 2007), but these conditions may impede passage of other species with different swimming abilities.

- Fishways and fish ladders around dams in biodiverse tropical rivers show a strong tendency toward species selection, allowing passage of certain migratory species while truncating the distribution of relatively weak swimming species that nonetheless depend on seasonal dispersal mechanisms (Agostinho et al. 2007).

7.3.5.15.1 Culverts

Culverts can induce ecosystem fragmentation through effects on fish passage; the interruption of natural channel migration processes and channel configuration; altered transport of sediments, organic material, and large woody debris; and in some cases the creation of new habitat types that are inconsistent with the natural channel form.

Alterations to existing culverts fall into three categories:

> "Culvert removal" means complete removal of the culvert in conjunction with decommissioning of the roadway or flow control structure, or replacement of the culvert with a bridge.

"Culvert replacement" means taking a culvert out of a stream, and replacing it with a design that accomodates fish passage.

"Culvert retrofit" means modifying an existing culvert with baffles, internal weirs, or similar structural elements to enhance fish passage.

Addressing passage barriers at culverts to restore access to fragmented habitat is recognized as a priority issue in salmon habitat restoration strategy (Roni et al. 2002). From the perspective of existing conditions, improving fish passage at culverts must generally be viewed as having beneficial effects on ecosystem fragmentation. When comparing the effects of culverts to a natural stream baseline, only culvert removal projects have little to no potential to produce adverse ecosystem fragmentation effects. Even the most carefully designed culvert replacement or retrofitting project can produce some forms of ecosystem fragmentation.

- The culvert may not provide full fish passage, unintentionally imposing specific types of barriers.
- Fish passage may decrease over time due to design limitations.
- Improperly maintained culverts may become blocked by debris.
- Headcuts[3] induced or reinitiated by culvert removal or replacement can result in changes in channel geometry, such as incision, that affect habitat complexity. Headcut migration may cause channel incision and lateral and longitudinal habitat fragmentation. Such changes in channel morphology can impede fish passage.
- The culvert may not allow for the unrestricted downstream transport of woody debris and organic material, affecting habitat complexity and food web productivity in downstream reaches. Generally, this effect is associated with retrofitted culverts. Replacement culverts are generally less likely to produce ecosystem fragmentation effects because current design guidance favors approaches that mimic natural stream hydraulics ("stream simulation.")
- Headcut liberation and channel incision can also influence the recruitment, transport, and retention of sediment and LWD, leading to longer term impacts on habitat complexity. These impacts include altered storage and retention of sediment and particulate organic matter, as well as hydraulic simplification (which reduces the diversity of instream habitats available for fish). Channel incision may also alter the functional relationship between LWD and the stream channel. For example, spanning LWD that would be functional under natural channel conditions may not interact with surface water under the same range of

[3] "A headcut, sometimes called a knickpoint, is a vertical or near-vertical drop or change in elevation of a stream channel, rill, or gully." http://www.ars.usda.gov/research/publications/publications.htm?SEQ_NO_115=158547

flow conditions in a degraded channel. This would reduce the influence that woody debris has on habitat conditions in the stream channel.

If a culvert is providing grade control, replacement or removal of the culvert may result in the following intermediate-term responses (Castro 2003):

- Headcut migration upstream and subsequent deepening of the stream channel.
- Relatively higher channel banks that may exceed critical height, resulting in slope failure and bank erosion.
- Addition of sediment to the stream system due to erosion of the channel boundary.
- Disconnection of floodplains from active stream channels.
- Prematurely dewatered or disconnected backwater habitat.
- Locally increased channel slope and loss of pool habitat.
- Drainage of shallow aquifers affecting riparian vegetation.
- Meander cut-offs due to knickpoint migration across a meander neck caused by an increased elevation drop between the old floodplain and active channel bed.
- Deposition of large masses of sediment causing localized channel braiding and instability of the stream banks.

Culvert retrofits are intended specifically to improve fish passage, thereby addressing one component of ecosystem fragmentation. However, retrofitting typically will not reduce the fragmentation of ecological processes induced by the structure, and may exacerbate certain problems. For example, placement of internal weirs and baffles will decrease the hydraulic capacity of the culvert, which can create backwater effects upstream of the structure and lead to sediment deposition. This can interrupt sediment transport processes, leading to some degree of sediment starvation downstream of the structure.

Culvert retrofits are more prone to produce fish passage related stressors than culvert replacement. Successfully retrofitting a culvert for fish passage requires knowledge of the swimming performance and passage requirements of the full range of HCP species likely to attempt to navigate the structure. It may be challenging to produce a design that provides for the needs of all species of interest, meaning that some degree of ecosystem fragmentation may occur. Moreover, retrofitted culverts typically require regular maintenance to maintain function. When they are improperly maintained, fish passage performance is likely to decline significantly.

Studies have shown that flow velocity affects fishes' ability to pass culverts.

- Juvenile salmonids have been shown to respond preferentially to different velocity conditions when traveling downstream through weirs (Kemp et al. 2006), suggesting that structures designed without proper consideration of attraction flows may be ineffective.

- Flow velocity, exposure distance to excess flow velocity without hydraulic refuge areas, and other factors, can influence the ability of juvenile salmonids to effectively pass through fish passage structures (Behlke 1991).

- In a laboratory environment, juvenile fish moving through culverts were observed using low-velocity pathways within turbulent boundary layers and behind baffles. The pathways selected differed between the baffled and unbaffled test environments, and also potentially differed depending on flow rates in the baffled environment (Pearson et al. 2006). In some instances, juvenile fish passed culverts at higher mean velocities in the cross-section than the physiological limits of swimming performance would suggest. This indicates that fish adaptively select low-velocity pathways to navigate through culverts where possible.

- Powers and Bates (1997) studied the passage of juvenile coho salmon through culverts composed of several different materials and found significant differences in the velocities that permitted passage. Specifically, they noted that the turbulent boundary layer created by corrugated metal pipes appeared to create a lower velocity zone that enhanced passage relative to culvert pipes with smooth interiors.

- The presence of lower velocity zones within culverts has been confirmed by subsequent research (Ead et al. 2000; Pearson et al. 2006). Pearson et al. (2006) confirmed that simple sized-based extrapolation of swimming performance underpredicted the ability of juvenile coho salmon to pass culverts. A key factor appeared to be the ability of smaller fish to utilize lower velocity zones in the hydraulically complex boundary layer at the culvert surface. They recommended additional studies to confirm whether the design and discharge parameters that provided successful passage for larger individuals are applicable to smaller juveniles (e.g., 1.1–.6 inches [30–40 millimeters]) that migrate during spring flow conditions. It is important to note, however, that this work was conducted in a laboratory setting. It is not clear how any information gleaned from these studies would apply to a range of culvert designs and settings in the field.

In certain cases, culvert replacement or removal can eliminate or alter distinct wetlands formed by road-impounded wetlands. For example, the Olympic mudminnow is restricted to slack-water habitats in slow-moving streams, ponds, and wetlands with several centimeters of soft sediment substrate (Mongillo and Hallock 1999). Culvert removal could alter flow, channel geometry, and substrate conditions, reverting the impounded reach to a coarse-grained, free flowing condition (Naiman et al. 1988). This would eliminate habitat for this species. In such special circumstances, it may be desirable to design a culvert replacement that maintains the impoundment habitat.

Culverts have been shown to affect passage of nonsalmonid species. Warren and Pardew (1998) evaluated the migration of 21 warm water fish species including centrarchids (sunfish), cyprinids (minnows and suckers), and fundulids (killifishes) through four types of culverts in western Arkansas streams. They found that regardless of design, culverts restricted the movement of each species studied by at least an order of magnitude relative to natural conditions. This suggests that even carefully designed fish passage structures have the potential to impose passage barriers on HCP fish species when the knowledge of their specific passage requirements is limited.

In addition to effects on aquatic species, roads and flow control structures also have the potential to fragment foraging, migratory, and dispersal corridors used by nontarget aquatic, semi-aquatic, and terrestrial species. Researchers in the United States and Europe are currently investigating the utility of different culvert designs to provide migratory corridors for terrestrial species (Bates et al. 2008). It is conceivable that ecosystem fragmentation effects imposed by culverts on terrestrial species could result in indirect effects on HCP species. However, insufficient research has been conducted on this subject to assess the nature and extent of any indirect effects that may occur.

7.3.5.15.2 Fish ladders/fishways

Fishways can result in ecosystem fragmentation through a number of pathways. Because these structures are intended to improve passage, an inherent objective of their design is to reduce ecosystem fragmentation by promoting connectivity of habitats along the river continuum. Improved fish passage promotes additional benefits from ecological connectivity.

Fishways may unintentionally result in ecosystem fragmentation by imposing intentional or unintentional passage barriers. Passability may decrease over time due to design failure or improper maintenance. Alterations to fish passage may in turn alter the upstream transport of nutrients from distant sources, particularly marine-derived nutrients (e.g., in the form of salmon carcasses), affecting ecosystem productivity.

Many studies have identified structures that fail to provide adequate fish passage for the species they are intended to benefit, or that unintentionally limit passage of nontarget species (Agostinho et al. 2007; Boggs et al. 2004; Bunt et al. 1999; Caudill et al. 2007; Moser et al. 2000; Moser et al. 2002; Naughton et al. 2007). In many cases, fishways have been designed and installed without a definition of specific performance objectives, so their performance is difficult to rate (Cada and Sale 1993).

A fishway may initially function appropriately but may lose effectiveness over time if the structure becomes compromised by changing channel conditions or improper maintenance. As an example, the fishway around the hatchery weir at the Quilcene

National Fish Hatchery (Big Quilcene River, Washington State) has become increasingly less effective at passing winter steelhead due to the combination of cobble aggradation and high-flow velocity at the upstream exit of the weir, which redirects fish along a path that results in a high rate of "fallback" (fallback occurs when fishway exits are located in areas where high current velocities wash fish back over the barrier the passage structure is intended to bypass).

Structure design may also lead to unnecessary stress and energy expenditure by fish. For example, high "fallback" rates have been observed at fishways at Columbia River dams. When passage over eight dams was considered, 15 to 22 percent of adult Chinook and 21 percent of adult steelhead fell back over at least one dam (Boggs et al. 2004). Available evidence suggests that the migration delay and energetic costs imposed by fallback could lead to decreased survival and spawning success (Caudill et al. 2007). These structures can be redesigned to decrease the likelihood of fallback.

7.3.5.15.3 Weirs

Fish passage weirs may unintentionally result in ecosystem fragmentation by imposing intentional or unintentional passage barriers. Passability may decrease over time due to design failure or improper maintenance. Alterations to fish passage may in turn alter the upstream transport of nutrients from distant sources, particularly marine-derived nutrients (e.g., in the form of salmon carcasses), affecting ecosystem productivity. Weirs may create impoundment conditions that may alter the downstream transport of woody debris and organic material, affecting habitat complexity and food web productivity in downstream reaches.

Temporary weirs are, by design, limited in effects. These structures are typically semipermiable to water, wood, sediment, and organic debris transport while in place, and transparent to these processes when not in use. The degree to which these structures alter ecological connectivity is expected to be minor in extent and limited to short-term construction and operational effects.

Permanent barrier weirs are expected to impose a broader suite of potential effects on HCP species.

Weirs and other structures intentionally designed to prevent or limit fish access have been broadly employed to restrict exotic species invasions. Competition for forage and habitat and genetic introgression and hybridization with non-native species have been demonstrated to adversely affect native salmonid populations (Reiman et al. 2006; Shephard et al. 2002; Utter 2001).

- Man-made barrier structures have been installed in many tributaries in the Laurentian Great Lakes to limit the distribution of sea lamprey (McLaughlin 2006), with the understanding that these barriers may unintentionally limit migration and dispersal of native fish species and invertebrates such as freshwater mussels that rely on fish for part of their life cycle.

- In the Western U.S., barrier weirs have been successfully employed to prevent habitat recolonization by brook trout following their eradication, supporting recovery of depressed westslope cutthroat and bull trout populations (Shephard et al. 2002).

Longitudinal connectivity is the most documented type of ecosystem fragmentation attributed to weirs in the literature.

- Weirs result in delayed migrations of fish that need to navigate over them (Chanseau et al. 1999).
- In Denmark, Atlantic salmon and brown trout losses increased due to delayed migrations and increased predation while these fish were trying to negotiate weirs (Aarestrup and Koed 2003).
- A similar result was observed with brown trout in the Bidasoa River in Spain (Gosset et al. 2006).
- In Australia, radio-tagged fish were removed from a river after passing over (and under) weirs and were placed back downstream of the structures. When faced with passing the weir a second time, few of the fish did, with most trying to avoid it altogether (O'Connor et al. 2006).
- Some studies have shown that restricted upstream movements are dependant on fish size, with larger fish able to pass small weirs more easily than smaller fish (Baker 2003; Winter and Van Densen 2001).

7.3.5.16 Fish Screens

Fish screens are intended to block the movement of fish and other organisms out of their habitat with water withdrawn from the system. (Water withdrawal itself is regulated by Ecology and is not subject to approval under the HPA program.) Fish screens are intended to prevent fish entrainment and loss caused by unscreened intakes and diversions associated with flow control structures such as dams and weirs. In this sense, they impose a passage barrier that should be considered beneficial. However, due to design limitations or improper maintenance and operations, fish screens can produce unintended adverse effects on fish passage. Fish screens can delay migration, exposing fish to increased stress and predation-related mortality; or may impose timing- or size-specific selection pressures on affected fish species.

Fish screens may impose unintended selection pressures by providing effective downstream passage of juveniles during only part of the downstream migration (Kiefer and Lockhart 1995). Kemp et al. (2006) found that flow velocity and depth strongly influenced the behavior of juvenile fish entering bypass systems at Snake River hydroelectric facilities. While this study did not explicitly evaluate the effects of screens, it nonetheless demonstrates the sensitivity of certain HCP species to parameters that are important in screen design. The potential for these parameters to influence species-specific screen performance is also a concern. Sweeping flows[4] that function well for salmonids may not be suitable for other fish species such as dace (Cyprinidae) or lamprey (Close et al. 1998).

To the extent that they affect upstream fish passage, fish screens may also have the unintended effect of restricting the dispersal of HCP freshwater invertebrate species. This can occur in two ways. First, the structure may restrict the distribution of host fish, affecting the dispersal of parasitic larvae (Vaughan 2002; Watters 1996). Second, attraction flows may draw mussels and snails capable of crawling along the stream bottom to bypass channel outlets that restrict their further upstream movement. For example, certain freshwater mussel species are known to move at least some distance upstream, using their muscular foot and byssal threads (Vaughan 2002). Species such as California floater mussels may face demographic risks from the unintentional limitations on distribution because the effects of fish screens on their host-fish species (minnows and other cyprinids) are less well understood.

7.3.5.16.1 In-Channel Fish Screens

Many HCP fish species, such as herring, rockfish, pollock, cod, eulachon and longfin smelt have planktonic larvae that are dependent on wave and current patterns for transport to and/or retention in productive rearing areas such as estuaries. Highly fecund species that produce spatially variable planktonic spawn rely on current-driven transport and retention mechanisms for reproductive productivity (Hernandez-Miranda et al. 2003; Rooper et al. 2006; Sinclair 1992).

In-channel intake systems employing bankline screens in sheltered alcoves or embayments (in riverine, marine, or lacustrine environments) commonly employ pumped bypass systems because there is insufficient hydraulic head to operate a gravity-driven bypass. Planktonic eggs and larvae, or weak swimming or behaviorally driven fish species, may be drawn into fish screens by the inflow and become trapped (Bates 2008). Screen systems may bypass planktonic or weak-swimming organisms but return them to locations where prevailing currents draw them back into the intake embayment. This is likely to lead to elevated mortality through predation, starvation, unfavorable water quality conditions, or a combination of these effects (Sinclair 1992).

Ecosystem fragmentation occurs when organisms are trapped in embayments by ineffective screening and bypass systems, limiting dispersal to favorable rearing areas. Fish species that migrate along nearshore marine and lacustrine environments, such as juvenile anadromous salmonids, that are drawn repeatedly into bypass systems may experience delayed migration, with attendant effects on survival, growth, and fitness.

[4] "Sweeping velocity is the water velocity vector component parallel and ajacent to the screen face." National Marine Fisheries Service, Southwest Region. Fish Screening Criteria for Anadromous Salmonids. January 1997.

Bankline and other in-channel screen systems (e.g., Gunderboom[5] screens) attempt to limit this mortality by bypassing organisms back to the aquatic environment.

7.3.5.16.2 Off-Channel Fish Screens

Off-channel fish screens includes some unique design characteristics having their own potential to impose ecosystem fragmentation. Specifically, the additional increment of streamflows required for bypass system operation can modify channel and flow conditions in ways that fragment off-channel habitat. Moreover, bypass systems that discharge into blind side channels may create flow conditions that confuse migratory pathways.

The potential ecosystem fragmentation impact submechanisms potentially imposed by off-channel fish screens include the following:

- Passage and dispersal barriers: Bypass channel flows may attract upstream migrants, causing an unintentional migration delay. Sweeping flows in diversion channels may not be sufficient to draw downstream migrants into the bypass system, leading to unintentional delays in downstream migration or dispersal.

- Modified downstream transport of woody debris and organic material: Woody debris and organic material cleared from screen surfaces may not be returned to the aquatic ecosystem.

- Altered lateral habitat connectivity: Decreased flows within the bypassed reach may alter the connectivity to and availability of side-channel and off-channel habitats under lower flow conditions.

In certain circumstances, vegetation encroachment induced by bypass system operation may result in changes in channel form that can in turn fragment lateral habitat connectivity. Bypass systems that increase flow into existing natural side channels, or effectively create an artificial off-channel environment, can mitigate effects on habitat fragmentation in some cases. In highly hydromodified environments, this effect could be beneficial, increasing available habitat area and complexity.

While these effects are more commonly associated with structures that impose barriers to fish passage, fish screen structures may alter the downstream transport of wood and organic materials when measured against the natural stream condition or the environmental baseline. Certain off-channel screen designs, such as traveling belt screens, incorporate debris collection trays that isolate wood and organic material from the stream channel. Other off-channel screens may be prone to debris jams on the screen or in bypass systems that require manual clearing. These materials may be returned to the channel as an operational practice, or may be disposed of upland. In the latter case,

[5] Examples do not constitute a recommendation from the Washington Department of Fish and Wildlife.

there would be an incremental decrease in the amount of wood and organic material available to downstream reaches.

In Washington State, a concerted effort to design and broadly implement diversion screening requirements started in the 1940s, and major upgrades started in the 1980s (McMichael et al. 2004, Schille personal communication March 2009). This cooperative program has promulgated research-based design guidance and monitoring criteria that are in broad use. While this program has produced fish screens that have undoubtedly reduced entrainment-related losses of anadromous and resident fishes, some of these screens have imposed unintentional barriers to fish passage (Carter et al. 2003; McMichael and Chamness 2001; Vucelick and McMichael 2003; Vucelick et al. 2004). These barriers can take the form of physical conditions that delay upstream or downstream migration, potentially coupled with conditions that increase predation risk, or that impede migration entirely during certain flow rates.

In the case of juvenile salmonids, downstream migration delays can occur when improperly designed screens may fail to provide sweeping flows adequate to draw fish into the bypass channel. For adult fish, upstream migration delay can be caused by false attraction to bypass outfalls or by locating the bypass discharge point in proximity to the diversion intake, causing fish disoriented by exiting the bypass system to enter and fall back through the bypass.

Migration delays and nonlethal stressors may increase predation exposure, resulting in increased mortality rates. For example, shear stresses associated with passage through dam bypass channels have been associated with temporary disorientation that leads to increased mortality rates (Cada et al. 1999; Mesa 1994). While it is unclear whether stresses occurring in bypass channels reach levels sufficient to increase predation vulnerability (Cada et al. 2003), WDFW guidance cites this potential as an important consideration in bypass channel design, noting that outlets should be located where conditions are unfavorable for predators to loiter (WDFW 2001a). Such steps may help to mitigate predation losses. For example, Mesa and Olson (1993) found that flow velocities in excess of 39–51 inches/second (100–130 centimeters per second [cm/s]) were likely to exceed the sustained swimming speed of predatory northern pikeminnow (referred to as squawfish by the authors), and cited this range of flow rates as useful guidance for locating bypass channel discharge points.

Fish screens can also unintentionally affect passage success based on life-history stage (i.e., by size). Because juvenile salmonids migrate downstream in many river systems, they must travel past numerous diversions with screens of various designs. Off-channel screens must provide sufficient sweeping flows to draw fish into bypass channels without significant migration delays. Suitable sweeping flows may vary by species and by size. For example, juvenile salmonids have been shown to respond preferentially to different velocity conditions when traveling downstream through weirs (Kemp et al. 2006). Attraction velocities must be balanced against other factors such as avoiding impingement while achieving the desired diversion rate. Design guidance focused on achieving this balance for juvenile salmon may be suitable for some other species, such as bull trout (Zydlewski and Johnson 2002), but may or may not provide adequate protection for other fish species with different swimming or biological requirements (Bestgen et al. 2004; Blackley 2004; Close et al. 1998; Moyle and Israel 2005; Peake 2004). A basic premise of screen and bypass design is that fish are actively migrating and seeking a downstream migration path (Bates 2008). This premise may be inappropriate for fish that are passively dispersing rather than migrating.

Upstream migration and other movements within freshwater rearing habitats are also recognized as important factors to consider when designing fish screens. Direct study and review of available research have demonstrated that juvenile salmonids (both anadromous and resident species) are seasonally migratory, moving between refuge and rearing habitats (Bolton et al. 2002; Kahler and Quinn 1998; Kahler et al. 2001). While fish screens are less of a factor than the flow control structures they are typically associated with, certain designs may nonetheless have undesirable effects on upstream passage. Specifically, dedicated bypass channel flows may unintentionally attract upstream migrants into impassable side channels (WDFW 2001a). For example, this may delay dispersal to habitats suitable for summer rearing. Proper design may avoid this unintended impact.

7.3.5.17 Outfalls

Ecosystem fragmentation would be minimally affected by outfalls. Habitat connectivity will likely remain intact for most outfalls, both submerged and exposed. If an outfall crosses a stream or river such that it interferes with downstream flow, then impacts related to upstream–downstream connectivity will be important. If an outfall is placed along the bank of a stream or river, it could potentially exclude access to side channel and floodplain habitat. When exposed outfalls are located such that they terminate at the riverbank and are located above the stream, their main impact is the result of water chemistry changes. Some studies have shown that species diversity and composition changes can be minimal above and below an outfall (Fries and Bowles 2002; Pillard 1996). These studies suggest that ecosystem fragmentation with respect to altered species composition and diversity is likely minimal.

Marine outfalls may cause ecosystem fragmentation as a result of altered wave energy, current velocities, and nearshore circulation. The degree of these impacts depends on the volume of discharge and local mixing and may result in impacts on some HCP species

7.3.5.18 Intakes and diversions

Intakes and diversions may alter flow, which can influence habitat connectivity and lead to habitat loss. Depending on the size of the diversion, changes in flow may be minimal or significant. Reduced discharges from diversions can reduce floodplain connectivity for those fish and invertebrates using these habitats (Kingsford 2000). Reduction in flow has also been shown to concentrate macroinvertebrates as a result of the reduction in available habitat, leading to increases in insect densities in the system (Dewson et al. 2007). Water diversions have been shown to alter temperature, which has been shown to change macroinvertebrate communities (Miller et al. 2007).

Intakes alter food webs and predator-prey interactions. Alteration of natural food webs could change species composition which, in turn, may allow the invasion of exotic species. Intakes and diversion can remove important resources from the aquatic ecosystem when they are entrained in the water column. Predator-prey relationships are altered when drifting insects and larvae are entrained in intake waters, effectively removing food resources from downstream organisms.

- Benstead et al. (1999) showed that entrainment of freshwater shrimps in Puerto Rico can vary from 34–62 percent of drifting larvae based on field data and a flow model using 30 years of discharge data.

- In Hawaii, McIntosh et al. (2002) studied the impacts of diversions on riffle macroinvertebrate communities. The authors collected larval populations upstream and downstream of diversions and showed that total density decreased by 54 percent, thereby affecting trophic interactions downstream.

7.3.5.19 Pipelines and Cables

Love and York (2005) examined pipelines serving oil wells in the Santa Barbara Channel in California. Along the pipeline, the diversity and number of both fish and invertebrates were much higher than on the adjacent seafloor. The hard substrate of the pipeline was colonized by numerous sessile and motile invertebrates, and fish densities were six to seven times greater than on the adjacent seafloor. Rockfish comprised 84 percent of the fish species and represented 22 species. Most were juveniles or represented species that are small at maturity.

Kogan et al. (2003) examined a submarine cable running from Half Moon Bay to Pioneer Seamount in California, a distance of 59 miles (95 kilometers). In the seven years the cable had been in operation, most of the cable had been buried by sediments along the continental shelf, where water depths range up to approximately 390 feet (120 meters [m]), except over areas of rocky substrate. Anemones, echinoderms, and sponges had colonized the cable and were conspicuous in areas where the cable provided the only available hard substrate. In three of nine survey locations, flatfish and rockfish congregated near the cable. The cable had no measurable effect on benthic infauna.

7.3.5.20 Beaver Dam Removal

The draining of beaver dam impoundments represents a significant modification of the aquatic environment which fragments ecological connectivity in the longitudinal, lateral, and vertical dimensions. These impact mechanisms have been demonstrated to produce a number of ecological stressors with the potential to impose a risk of take on HCP species.

7.3.5.20.1 Altered Longitudinal Connectivity

On initial consideration, breaching of beaver dams may appear to improve longitudinal connectivity in riverine systems. Beaver dams represent a potential barrier to fish passage as well as a zone of hydraulic complexity which sequesters sediment, wood, organic material, and water. However, beaver dams are typically semipermiable and do not pose total barriers to fish passage. Early research suggested that beaver dams may serve as barriers that are detrimental to resident species (Pollock et al. 2003). However, more recent research has indicated that longitudinal connectivity is only seasonally altered and that beaver activity is an overall net benefit to aquatic organisms (Pollock et al. 2003; Rolauffs et al. 2001; Sigourney et al. 2006). Beaver dams are usually built within free-flowing reaches so the presence of the dam itself creates pool habitat which is utilized by many of the HCP species, notably juvenile coho salmon (Pollock et al. 2004). The juveniles are present in beaver impoundments in part because the low energy environment of the impoundment provides refuge and foraging habitat (Rolauffs et al. 2001). Although beaver dams do create a change in head at the dam face which could impede fish passage, dam structures are complex and relatively permeable under a range of flow conditions (Naiman et al. 1986). Consequently, beaver dams do not present a barrier to passage comparable to man-made dams.

As a natural feature of the landscape, the hydraulic and structural complexity provided by beaver dams supports a broad array of species during different stages of their life history, including HCP species. The distribution of these features along a longitudinal gradient in riverine ecosystems is an important measure of ecological connectivity, particularly for species such as coho salmon that prefer slow water habitats like beaver ponds for rearing habitat. Altering the longitudinal connectivity of complex, diverse habitats in a riverine environment by draining beaver ponds represents a form of ecosystem fragmentation. Beaver dam removal or modification may result in increased longitudinal connectivity, but at the cost of reduced availability of suitable habitats for those species dependent on the impounded environment.

Beavers alter their environments by modifying riparian vegetation and the channel base level. These alterations lead to an increase in aquatic habitat patches (Johnston and Naiman 1990).

Much of the research concerning ecosystem fragmentation and impoundments has focused on the impacts of dam presence and not dam removal. The creation of a reservoir through damming turns the impounded section of the river into a slow-moving, lentic habitat and alters the species composition of the river (Grubbs and Taylor 2004). Lake-adapted species may begin to flourish and riverine biota may become more susceptible to displacement. For example, in the Snake River in Washington, the combination of a series of 4 large reservoirs has contributed to the increase of salmonid predator densities (Wik 1995). This same phenomenon has been noted in beaver ponds, where introduced predatory species have been shown to flourish (Pollock et al. 2003). Despite this, high salmonid abundance has been noted in beaver impoundments (Leidholtbruner et al. 1992; Pollock et al. 2003; Pollock et al. 2004; Ray et al. 2004; Sigourney et al. 2006). With the removal of a beaver dam, lentic habitat will be converted to lotic habitat and a corresponding shift in the community structure will ensue.

Although beaver impoundments have been shown to be home to over 80 North American fish species (Pollock et al. 2003), studies have shown that beaver dams can function as seasonal barriers to fish movement (Murphy et al. 1989; Schlosser 1995).

7.3.5.20.2 Altered Terrestrial and River-Floodplain Connectivity

There is unanimous agreement that beaver impoundments increase lateral terrestrial-aquatic connectivity. Beaver dams raise the water surface elevation within the channel and inundate adjacent floodplain habitat (Westbrook et al. 2006). Lateral connectivity of the channel with its floodplain is increased upstream and downstream of beaver dams (Westbrook et al. 2006). Beaver ponds create and also increase access to floodplain habitat. The removal of beaver impoundments will sever this connection and reduce the quality of habitat for many of the HCP species. Due to abundant food resources and habitat which is protected from the high velocities associated with flooding events, the inundated perimeters of beaver ponds are ideal habitat for many of the HCP species (Pollock et al. 2003).

Shallow flooded riparian areas are some of the most productive habitat within a watershed (Bunn et al. 2003; Junk et al. 1989; Schemel et al. 2004; Sommer et al. 2005; Sommer et al. 2001) and, consequently, beaver dam construction increases stream (Naiman et al. 1994) and riparian (Duke et al. 2007) productivity. Beaver impoundments flood adjacent riparian vegetation and create a hydraulic conduit for terrestrial organic matter to enter the channel. This additional carbon input combined with high retention caused by the structure of the dam and increased solar input from canopy loss, are the drivers of elevated productivity in beaver impoundments. With the removal of a beaver dam, the organic matter is exported and the terrestrial-aquatic linkage is weakened. This will lead to reduced food resources in the waterway and an associated impact on HCP species.

The draining of beaver dam impoundments eliminates open water habitats and causes the channel system to withdraw from riparian and floodplain areas. Depending on where the stream channel stabilizes in the impoundment area, riparian habitats may be separated from the channel by open ground. This effect fragments the channel from floodplain habitats, reducing the connectivity between terrestrial and aquatic habitats. The reduced availability of these productive habitats may limit survival, growth, and fitness of those species that utilize the affected riverine habitats. An additional effect of is the vulnerability of disturbed habitats to invasion by exotic plant species. Exposed impoundment beds are likely sites for colonization by invasive species. Once these species become established, they may create a barrier to riparian recovery and a dispersal source for additional colonization. Invasive species may reduce the suitability of floodplain and riparian habitat for refuge, food production, and other ecological functions. These effects would also be considered likely to limit the survival, growth, and fitness of species that utilize the affected riverine habitats.

Table 7-4 [adapted from (Pollock et al. 2003)] shows the relative abundance of several fish species that may occur in beaver impoundments in Washington.

Table 7-4. Fish species known to utilize Washington beaver pond habitat.

Species	Common Name	Abundance	Comment
Oncorhynchus clarkii	Cutthroat trout	C	HCP species
Oncorhynchus kisutch	Coho salmon	C	HCP species
Oncorhynchus nerka	Sockeye salmon	C	HCP species
Salvelinus malma	Dolly Varden char	C	HCP species
Oncorhynchus mykiss	Steelhead	U	HCP species
Oncorhynchus mykiss	Rainbow trout	U	HCP species
Oncorhynchus tshawytscha	Chinook salmon	U	HCP species
Oncorhynchus gorbuscha	Chum salmon	O	HCP species
Cottus spp.	Sculpins	LC	
Gasterosteus aculeatus	Threespine stickleback	LC	
Prosopium spp.	Whitefish	LC	
Lota lota	Burbot	C	
Prosopium williamsoni	Mountain whitefish	U	
Catostomus commersoni	White sucker	C	
Phoxinus eos	Northern redbelly dace	C	
Culaea inconstans	Brook stickleback	C	
Hybognathus hankinsoni	Brassy minnow	C	
Phoxinus neogaeus	Finescale dace	C	
Pungitius pungitius	Ninespine stickleback	C	
Notemigonus crysoleucas	Golden shiner	LC	
Margariscus margarita	Pearl dace	O	
Cyprinella lutrensis	Red shiner	U	Not native
Esox americanus	Redfin pickerel	C	Not native
Esox niger	Chain pickerel	C	Not native
Ameiurus melas	Black bullhead	C	Not native
Lepomis auritus	Redbreast sunfish	C	Not native
Lepomis cyanellus	Green sunfish	C	Not native
Lepomis gibbosus	Pumpkinseed sunfish	C	Not native
Lepomis gulosus	Warmouth	C	Not native
Lepomis marginatus	Dollar sunfish	C	Not native
Lepomis punctatus	Spotted sunfish	C	Not native
Phoxinus phoxinus	Minnow	C	Not native
Pimephales promelas	Fathead minnow	C	Not native
Salmo trutta	Brown trout	C	Not native
Salvelinus fontanilus	Brook trout	C	Not native
Esox lucius	Northern pike	LC	Not native
Micropterus salmoides	Largemouth bass	LC	Not native
Ameiurus natalis	Yellow bullhead	U	Not native
Ameiurus platycephalus	Flat bullhead	U	Not native
Ictalurus nebulosus	Brown bullhead	U	Not native
Lepomis humilis	Orangespotted sunfish	U	Not native
Lepomis macrochirus	Bluegill	O	Not native

Source: Pollock et al. 2003.
C = common, LC = locally common, U = uncommon, O = occasional.

7.3.5.20.3 Altered Fish and Invertebrate Habitat

The primary impact on fishes associated with beaver dam removal is loss of foraging, refuge, and rearing habitat. Secondary impacts result from elevated suspended sediments and related stressor conditions during and subsequent to dam removal. These ephemeral impacts are short-term to intermediate-term in duration, and the resulting effects on aquatic species (including HCP species) are predominantly due to changes in the availability of suitable habitat and foraging opportunities, and behavioral responses to stressor exposure (Thomson et al. 2005). Increased nutrient and pollutant export associated with a single beaver dam removal will most likely not affect fishes, but the cumulative impact of channel simplification from the pre-Columbian era until present day has had a profound effect on nutrient and pollutant spiraling in fluvial systems (Wohl 2004), and must be taken into account when assessing potential impacts associated with any channel simplification activity such as beaver dam removal.

No studies have addressed the impact of beaver dam removal on HCP invertebrate species. There have, however, been studies which have addressed macroinvertebrate response to the removal of man-made dams. Research has indicated that dam removal will result in a significant decrease in downstream macroinvertebrate density for at least 1 year following removal (Stanley et al. 2002; Thomson et al. 2005). Given the habitat preferences of the California floater, Western ridged mussel, and the Great Columbia River spire, these species may inhabit beaver impoundments and the reaches immediately downstream (WDNR 2006b). The removal of a beaver impoundment would strand upstream invertebrates and potentially bury downstream individuals. Thus the construction phase and the sediment export following removal would be the primary impact mechanisms for invertebrates.

7.3.5.21 Spawning Substrate Augmentation

Spawning substrate augmentation leads to the creation of suitable spawning habitat. Suitable habitat has a variety of characteristics including desirable depths and velocities, and a high rate of hyporheic exchange. An ancillary benefit of spawning substrate augmentation is that connectivity with adjacent floodplain environments may be increased with an associated increase in bed elevation.

7.3.5.21.1 Altered Groundwater-Surface Water Interactions

The primary goal of gravel augmentation is to create suitable spawning habitat both in terms of depth and velocity as well as hyporheic exchange through the gravels. Hyporheic exchange brings oxygen-rich waters into the gravels which promotes spawner embryo survival (Heywood and Walling 2007). Spawning chum and Chinook salmon have been found to preferentially select spawning sites where water is either upwelling or downwelling (Geist et al. 2002) and where benthic dissolved oxygen is elevated (Geist 2000). Also, bull trout redd distribution and abundance have been found to be influenced by hyporheic and groundwater-surface water exchange (Baxter and Hauer 2000). This indicates that fish select for areas with high hyporheic exchange (Mull 2005). Gravel augmentation has been shown to increase hyporheic exchange (Merz and Setka 2004), and this helps to explain why fish are attracted to augmentation sites (Merz and Setka 2004; Mesick 2002).

An active hyporheos not only provides biogeochemical benefits to fish but also to macroinvertebrates. In a study of a gravel augmentation on the Mokelumne River, California, the standing crop, as measured by macroinvertebrate densities and dry biomass, was significantly higher in enhancement sites 12 weeks after augmentation than in unenhanced sites and remained so over the following 10 weeks (Merz and Chan 2005). Thus, it would appear that augmentation may not only provide spawning habitat but also food resources for emerging fry.

7.3.5.21.2 Altered Lateral Connections Between Rivers and Floodplains

Although the goal of spawning gravel enhancement is to improve benthic habitat, an ancillary benefit may be increased lateral connectivity with adjacent floodplains. Miller and Benda (2000) monitored debris flow sediment wave propagation in the South Fork of Gate Creek, Oregon and found that sediments cause vertical accretion of the valley floor due to increased overbank flooding depositing material across the floodplain. Gravel augmentation will be on a much smaller scale than a debris flow but the same processes may be applicable.

Spawning substrate augmentation may increase allochthonous carbon budgets in restored channels. Floodplain connectivity also creates fish forage and refuge habitat. Gravel augmentation below dams could be combined with flow management to induce periodic floodplain connection.

7.3.5.22 In-channel and off-channel habitat creation or modification

Habitat creation or modification is meant to ameliorate the impacts associated with ecosystem fragmentation.

7.3.5.22.1 Altered Lateral Connections Between Rivers and Floodplains

Depending on the project, in-channel habitat modifications may or may not increase river-floodplain connectivity. Projects that increase local base level through increased channel roughness or constriction may locally increase the potential for flooding (Young 1991) and thus increase aquatic terrestrial resource exchange and off-channel habitat accessibility. However, projects that do not alter channel hydraulics to such a degree will likely not increase river-floodplain connectivity.

Off-channel habitat modification will always be associated with increased lateral connectivity within the river corridor. Side-channel, slough, and floodplain pond creation and reconnection will promote the distribution of channel waters across the width of the valley floor and in the process impede flows (Wyzga 1996), increase organic matter recruitment (Tockner et al. 1999; Valett et al. 2005), and provide access to valuable foraging and rearing habitat (Henning et al. 2006). It has been estimated that in the Skagit Valley, 41 percent of sloughs and 31 percent of small tributary habitat has been lost to channelization for agricultural purposes (Beechie et al. 1994). This highlights the importance of rehabilitating off-channel habitat in Washington’s waterways. 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 are vital rearing habitat (Hall and Wissmar 2004; Sommer et al. 2005) and important sources of organic material for the channel (Tockner et al. 1999).

7.3.5.22.2 Altered Groundwater-Surface Water Interactions

Many in-channel and off-channel habitat modification projects result in an increase in flowpath complexity. Boulder placement creates divergent flow, rock weirs force water through pool-riffle transition zones, and side channels increase hyporheic exchange through bars and islands (Tonina and Buffington 2007).

Increased vertical exchange between surface and subsurface waters will 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 salmonids 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. 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).

7.3.5.22.3 Altered Habitat Complexity

The increased habitat complexity which is a goal of most in-channel habitat modification will, in theory, have a positive impact on aquatic species. However, the success of an individual project can not be guaranteed and in-channel restorations to date have not been thoroughly monitored (Bernhardt et al. 2005) and have been applied with mixed success (Babcock 1986; Frissell and Nawa 1992; Moerke and Lamberti 2004; Roper et al. 1998). Consequently, the potential benefits of in-channel restoration may not outweigh the impacts associated with the construction phase and potential for project failure.

7.3.5.23 Riparian planting, restoration, or enhancement

A primary goal of riparian planting is to create mature forests where they have been removed and, to the extent possible, rehabilitate the complex dynamic between the channel and adjacent vegetation. Channel restoration through riparian planting develops on a time scale which is much longer than other restoration methods. However, once vegetation has become established, bank roughness will increase and flood water velocity will decrease. This will, in turn, promote overbank flooding of riparian areas and increase connection with floodplain environments. Mature riparian vegetation will increase allochthonous input and augment aquatic food webs (Wipfli 2005). It has been shown that in the Pacific Northwest the relationship between riparian vegetation, instream wood, and channel geomorphology is complex and essential to natural system functioning. Riparian forest structure and distribution is controlled by catastrophic processes such as flooding, landslides, and wind storms. The associated recruitment of felled trees alters channel form and redistributes flow paths, creating new zones of deposition and vegetation establishment (Fetherston et al. 1995). In this way the vegetation influences the channel while channel response influences the vegetation, resulting in a complex productive system in which native aquatic organisms thrive.

7.3.5.24 Wetland creation, restoration or enhancement

The creation, restoration or enhancement of wetlands is meant to promote terrestrial and aquatic connectivity. Wetlands are ecotones between terrestrial and aquatic environments (Mitsch and Gosselink 2000). Estuarine marshes moderate the connection of terrestrial resources to the open sea (Tanner et al. 2002). These areas are highly productive, providing a wide range of food sources to littoral fishes. The elimination of marshes decreases channel complexity and reduces the productivity of the nearshore zone (Ferraro and Cole 2007; Hood 2004).

Years of restoration efforts have focused on increasing spawning habitat in upland systems, yet the resultant increased populations will not thrive if there is not adequate rearing habitat to support the population. It has been suggested that density dependent mortality, that is the mortality of fishes due to too many individuals and not enough habitat, is a factor in both the Skagit and Duwamish Rivers (Greene and Beechie 2004). This indicates that estuarine wetland rehabilitation and the increased rearing habitat availability associated with it will be vital to the rehabilitation of degraded fisheries in the State.

Several researchers have pointed out that the complexity of undisturbed systems is not easily recovered from altered environments (Simenstad et al. 2006; Simenstad and Thom 1996; Thom et al. 2002; Williams and Orr 2002). Subsidence of pre-development wetland areas during times when land-use was intensive means that many restored areas are now too low to provide the proper physical conditions (Thom et al. 2002; Williams and Orr 2002). While this problem can be pronounced in settings where the sediment supply is limited, most geomorphic situations where estuarine marshes are found in Washington State exhibit large sedimentation rates [e.g., the Skagit River: (Hood 2006)] where this issue is either not applicable or ameliorated after only a few years (Thom et al. 2002).

7.3.5.25 Eelgrass and other aquatic vegetation restoration/ enhancement

Because of its modest hydrogeomorphic impact, eelgrass planting is not expected to fragment existing ecosystems. Eelgrass meadows are one of the most productive environments in the temperate coastal ocean (Ferraro and Cole 2007; Phillips 1984). These meadows are host to a wide variety of organisms and thereby have the capability to connect less productive environments.

7.3.5.26 Trap and haul

Trap-and-haul programs are somewhat effective approaches to providing fish passage around man-made barriers. Ideally, this approach would be used as an interim measure until volitional passage around the barrier can be established (e.g., by removal of the barrier or by construction of a fishway, ladder, or other type of passage structure). This approach has been recommended to support conservation of native salmonids.

Fish trap-and-haul activities have the potential to impose three specific forms of ecosystem fragmentation, all specifically related to the selective effects on fish that they intentionally or unintentionally impose:

- Passage barriers: Several forms of passage barriers may occur (e.g., operational challenges may result in failure to successfully pass fish in a given year), and unintentional selection pressures (e.g., size, run timing) may be imposed on the affected population.

- Modified upstream transport of allochthonous nutrients: Trap-and-haul programs will affect the upstream transport of nutrients by the affected organisms.

- Alteration of migratory patterns: Trap-and-haul operations may introduce fish into tributaries they did not originally occupy, or release fish upstream of natal streams, frustrating migration behavior by bypassing olfactory cues used in homing.

Alteration of migratory patterns is a unique impact imposed by the trap-and-haul subactivity type. While trap-and-haul programs are intended to mitigate or address passage barriers, in certain cases these programs may alter or frustrate the migratory behavior of the target species with unintended effects on their viability.

- Toutle River Chinook, coho, and steelhead were forced to alter their migratory pathway by the heavy load of ash delivered to the system by the 1980 eruption of Mount St. Helens. Subsequent to the eruption, a sediment retention structure was placed on the North Fork Toutle River to intercept mass wasting. WDFW (in cooperation with the U.S. Army Corps of Engineers) has operated a trap-and-haul program to pass adult Chinook, coho salmon, and steelhead around the structure, which is a complete barrier to passage. However, due to access issues, the fish must be released several miles upstream of former mainstem and existing tributary spawning and rearing areas. These populations adopted alternate spawning locations in other watersheds and recolonized their former habitats after it had recovered sufficiently.

- Lake Washington basin Chinook salmon and steelhead historically migrated into the Cedar River and other tributaries from Elliot Bay via the Black River by way of the Duwamish River. The creation of the Lake Washington Ship Canal created a new entrance to the Lake at Shilshole Bay and dewatered the original migratory path through the Black River. Within a period of approximately 5 years, the native salmonid populations had adapted to this alteration and today access the lake and its tributaries through the ship canal.

- Hinson et al. (2007) examined the migratory behavior of coho salmon and steelhead released in non-natal tributaries using radiotelemetry and found that the released fish did not migrate to their birth streams as anticipated. In effect, the release location has altered the migratory pathway for the affected stocks, increasing the travel distance to their habitats by several miles and requiring adaptation to new habitats.

- Schmetterling (2003) studied the behavior of tagged bull trout and westslope cutthroat trout transported above Milltown Dam on the Clark Fork River to determine the likelihood of reoccupation of historic habitats. All the test subjects migrated at least some distance upstream, and he found that some individuals moved upstream as far as 62 miles (100 kilometers) or more. Based on these findings, Schmetterling (2003) concluded that a trap-and-haul program could be used to initiate recovery of adfluvial populations while options for volitional passage were being decided.

The fish passage related effects are more difficult to assess and potentially more significant. Even the most carefully operated trap-and-haul program has the potential to introduce some type of selection pressure on the affected population, which could alter genetic diversity. Because the selection pressures imposed are associated with artificial environments, these changes are likely to be detrimental.

The extent to which migration delays caused by alteration of migratory pathways affect fish will depend in many respects on the specific life history and physiology of the species affected. Salmonid species that enter river systems sexually immature and spend lengthier periods in fresh water, such as spring- and summer-run Chinook and summer-run steelhead, are likely to be less prone to adverse effects than sympatric ocean type races. These types of salmonids enter their natal streams ready to spawn; therefore, their reproductive success is more sensitive to the effects of migration delay.

Consider that summer-run steelhead populations in the interior Columbia Basin migrate several hundred miles to reach natal streams. In doing so, individual fish from these populations may explore non-natal streams over periods lasting from days to weeks and may migrate upstream for considerable distances (tens of miles or more). For example, steelhead from the Clearwater River basin, Idaho, are commonly caught by anglers in the Deschutes River in Oregon 10 or more miles upstream of its confluence with the Columbia River. In contrast, ocean-type fall-run Chinook in Puget Sound enter their natal streams essentially ready to spawn, suggesting that delayed migration would impose greater consequences on reproductive success.

The effects of migratory corridor alteration on HCP invertebrate species are expected to be limited. Alteration of the migratory path of fish species targeted by trap-and-haul programs would have no discernable effects on marine invertebrate species. Effects on giant Columbia River limpet and great Columbia River spire snail, which are not directly linked to fish migration patterns by life history, would be similarly unaffected. In contrast, alteration of fish migratory pathways could alter the dispersal of the glochidia larvae of western ridged mussels, potentially introducing these species into new habitats. However, as most trap-and-haul programs are transporting fish within their original ranges, the extent of these effects is considered to be minimal.