CHAPTER 5. FRESHWATER HABITATS

> *"Maintaining a rich diversity of Pacific salmon genotypes and phenotypes depends on maintaining habitat diversity and on maintaining the opportunity for the species to take advantage of that diversity" (Healey and Prince 1995).*

PHYSIOGRAPHY OF THE COLUMBIA RIVER

The Columbia River is one of the larger rivers of the world (Table 5.1) and also one of the most developed with ten major hydroelectric dams on the main river within the United States (Table 5.2; Figure 5.1) The catchment basin encompasses many different environments and climates encompassed by the wet coastal, Cascade and Rocky Mountain ranges and the semi-arid Columbia Plateau, which lies in the rainshadow of the Cascades. The extreme environmental diversity of the Basin is underscored by the fact that the Columbia Basin includes parts of 18 of the 43 physiographic provinces or ecoregions identified for the western United States (Omernik, 1987). Runoff (Table 5.1) derives from snowpack in the headwaters and seasonal rainfall in the lower elevations and coastal areas.

The Columbia River system is composed of steep gradient headwater streams that coalesce to form the major tributary rivers of the basin. The tributary rivers flow through mountain valleys where large alluvial flood plains occur between deep canyon reaches. These complex alluvial flood plains occur within the river continuum from headwaters to mainstem confluence like beads on a string. They are important with respect to salmonid ecology because they provide critical habitats (described below) that are much less available within the constrained channels of many of the canyon reaches. On the Columbia Plateau the lower reaches of tributary rivers like the Deschutes and John Day are partially or completely constrained by ancient lava flows and flood plains are less well developed. The same is true for the much of the mainstem Columbia and lower Snake Rivers; the only segments of the mainstem with extensive flood plains occur in the Hanford Reach and near the confluence of the Umatilla, which is drowned by John Day Reservoir. All of the Columbia Gorge is constrained and now impounded. Most of the channel of the Columbia River on its coastal plain below the Gorge is constrained by revetments built since the 1920s and lateral movement of floodwaters occur only on very high flow years.

Prior to extensive regulation by dams, the river was a gravel bed system from headwaters to mouth, although sand sized substratum became progressively more common in a downstream direction. Pre-regulation photos of the mainstem river in the Columbia Gorge show large sand dunes along the river (JAS has the photos if they need to be included here). Gravel and cobble was deposited extensively on the intermontane flood plains during high flows. The constrained reaches slowed the flow of floods allowing sand, gravel and cobble, along with tree boles and rood wads, eroded upstream to be deposited in the alluvial reaches upstream of the constriction. This process of cut and fill alluviation created a wide variety of instream and floodplain features of many sizes and shapes. Gravel bars and associated features also occurred in the constrained reaches, except at rapids created by exposed bedrock.

The bed load of the river is now largely retained in reservoirs. Only the finest sediments associated with spring runoff and other flooding reaches the estuary, owing to retention behind the many dams that have been constructed in the basin (Table 5.2, Figure 5.1). The mainstem retains only one freeflowing segment, the Hanford Reach. Many of the tributaries also are regulated, either by high storage dams used for hydropower production and flood control or by low head diversion dams for irrigation withdrawals. Bypass devices for migrating fishes have been built only on the mainstem and tributaries below Chief Joseph Dam on the Columbia and Hells Canyon Dam on the Snake.

CHARACTERISTICS OF HIGH QUALITY RIVERINE HABITAT

Salmonid fishes of all species require cold, clean water for survival and growth, and clean, stable, and permeable gravel substrate, usually in running-water environments, for reproduction. The specific habitat requirements of various species are discussed in detail elsewhere (Salo, 1987; Groot and Margolis, 1991; Meehan, 1991; Rhodes et al., 1994). Hence, herein we summarize the major habitat requirements of various life stages.

Habitat for reproduction

Incubation of salmonid eggs and fry occurs within the interstitial spaces of alluvial gravels in the beds of cool, clean streams and rivers. Native species of salmon, trout, and whitefish in the Columbia Basin are all lotic (running water) spawners in alluvial reaches of rivers and streams, except for sockeye salmon and kokanee (land-locked sockeye) which historically spawned on shallow, groundwater-effluent shoals or beaches on isolated shorelines of deep, cold lakes (e.g., Redfish (ID), and Wenatchee (WA), Chelan (WA) Okanagan (BC) and Kootenay (BC) Lakes) or similar environments in tributary streams of the lakes e.g., (Evermann, 1895). A few sockeye populations and some kokanee populations that have residualized from stocking in non-native lakes e.g., Pend Oreille, ID (Rieman and Bowler, 1980). Introduced salmonids such as lake trout and brook trout in general are less dependent on high-quality, running-water habitats for reproduction than are salmonids native to the Columbia Basin.

The season of spawning, egg incubation, and fry emergence varies among species of salmonids, with many rivers and streams historically supporting both fall spawning (winter incubating) and spring-spawning (spring and early summer incubating) populations. The relative success of fall- vs. spring-spawning strategies can vary depending on climate and hydrologic regime, catchment stability and sedimentation, water temperature patterns, the relative influence and availability of groundwater efflux zones, and controls exerted by seasonal flow conditions and physical barriers on the ability of adult fish to gain access to spawning sites. In general, spring-spawning species (e.g., steelhead, rainbow and redband trout, and cutthroat trout) concentrate their reproductive activities in smaller, headwater streams and in spring snowmelt-fed streams. Reproduction of fall-spawning species (chum, chinook, and coho salmon and bull trout) occurs most frequently in alluvial reaches of larger streams and rivers where groundwater efflux strongly buffers local interstitial and surface water conditions. Long-term patterns in local variation in the seasonality of flow and sediment transport, the availability of clean, stable substrates, patterns in groundwater-surface water exchange, and thermal regime exert high-magnitude, density-independent effects on the survival and recruitment of salmonids that strongly constrain the abundance of all later life stages, including harvestable adults. Salmonid fish populations display a diversity of local adaptation of life histories and behaviors in concordance with this local environmental complexity. These components of the freshwater environment are highly vulnerable to alteration by most kinds of human activities and natural events.

Juvenile rearing and movements

Once emergence from the gravel is complete, young salmonids are mobile, which increases their individual flexibility to cope with environmental variation by seeking suitable habitat conditions. Mobility is limited, however, particularly for fry, so that suitable habitat and food resources must be available in proximity to spawning areas for successful first-year survival. Moreover, movement may come with high metabolic cost and high risk of mortality, such as through exposure to predators, unless movements are tied closely to patches of predictable, high-quality habitat. These habitats ideally afford low-velocity cover, a steady supply of small food particles, and refuge from larger predatory fishes, birds and mammals. Examples of such habitats include quiet-water areas, backwaters, and small spring-fed channels along stream margins, floodplain ponds and sloughs, and alcoves within structural complexes created by woody debris, bank structures and riparian vegetation or aquatic plants. These critical habitats are most abundant and structurally diverse on aggraded, floodplain reaches where they are created and maintained by cut and fill alluviation. Alluvial floodplains occur like beads on a string from headwaters to river mouth (Stanford and Ward, 1993), although floodplains in the Columbia River Basin are most complex in the middle reaches of tributary rivers owing to the entrenchment of the mainstem river channel. Pink salmon, which were never very common in the Columbia River, move quickly to the ocean after hatching and sockeye salmon move into lakes as small fry. However, these laucustrine-oriented species also require shallow resting habitats with cover from predators, as provided by the complex features of functional flood plains, during fry migration.

Natal (very young fry) salmonids typically feed on invertebrates and small vertebrates and, in high quality alluvial habitats, they can grow rather rapidly. As water temperature increases beyond about 15°C, metabolic costs escalate rapidly and available food resources support progressively lower densities of juvenile salmonids (Li et al., 1995). Summer temperatures in most Columbia River tributaries, particularly the floodplain reaches that have been extensively altered by human activities, typically far exceed this value and in many cases pass the lethal thermal maximum for salmonids (Rhodes et al., 1994, see discussion later in this chaper). Suspended sediments impair the ability of salmonids to see and capture prey, and accelerated deposition or transport of sediments on streambeds can deplete populations of stream invertebrates that are most important for salmonid growth.

Juveniles of some salmonid populations and species are known to successfully move long distances (many tens or even hundreds of kilometers) from their natal habitats, and some, such as pink, chum, some sockeye and fall or ocean-type chinook salmon, virtually are never resident; they move downstream after emergence progressively stopping to feed and grow in lower-velocity habitats created by eddies in constrained (canyon) segments and, in particular, the complex habitats of floodplains. Experimental studies with several salmonid species indicate directed movements or patterned migratory behaviors that are genetically determined, and these movements are closely tied to available habitats of various kinds. For example, juveniles in some populations in larger rivers tend to move downstream in late fall to seek wintering habitat in low-velocity backwaters of large floodplains or deep pools, whereas others tend to move upstream where wintering habitat is available in aggraded headwater areas (e.g., in beaver ponds).

Each local breeding population likely evolved site-and season-specific patterns of early-life-history behavior that allow juveniles to efficiently locate and exploit the locally available patchwork of habitat. For example, sockeye fry resulting from spawning in lake inlets move downstream to rear in the lake, while those spawned in the outlet usually move upstream to rear in the same lake (Brannon and (eds.), 1982). Lack of such a locally-adapted genetic heritage is one likely reason that hatchery-origin fish, including all forms of cultured and translocated fish and their offspring, typically exhibit lower fry to adult survival rates than indigenous fish of the same species, age and size (Ricker, 1972; Riddell and Legget, 1981), although total survival of some hatchery fish may be higher than wild fish (Shreamer 1995). Moreover, destruction or alteration of available habitat mosaics created by natural biophysical processes (e.g., as a consequence of cumulative effects of flow regulation and fine sediment, thermal and chemical pollution, and upland and riparian land misuse) almost always impairs the survival of indigenous fish by compromising their inherited ability to anticipate and "track" high quality habitats (Stanford et al., *in press*).

Long-distance migration of juveniles or sub adults downstream to lakes, rivers, or the ocean for maturation may intuitively seem maladaptive. However, migration can allow increased opportunities for access to concentrated food resources that allow rapid growth, permit escape from localized concentrations of predators or marginal habitats, and mediate longer life span and large body size which confers selective advantage. While some species retain a diversity of rearing strategies that allow them to persist in headwater populations even when opportunities for downstream migration are poor (e.g., steelhead, kokanee salmon), other species are completely dependent on long-distance migration for maturation and survival (other salmon, and to a lesser extent, bull trout). On the other hand some populations do not move much, staying in the same stream reaches or lakes throughout their life cycle e.g., bull trout in Upper Kintla Lake, MT: (Hauer et al., 1980). However, the great historical abundance of migration-dependent species in the Columbia River indicates this system has (until recently) provided habitat favorable for a wide array of anadromous and river-migrant salmonid life histories for many centuries. Owing to the complex physiography of the Columbia River, opportunities for adaptation to particular rivers and even river segments was historically high and, as noted above in Chapters 2 and 4, metapopulations were composed of suites of interactive, but locally-adapted, stocks.

Habitat for adult migration

After growth and maturation, salmonid adults generally return to natal spawning areas for reproduction. The timing of adult entry and movement in rivers and tributary streams, and even the size, shape, and strength of adult fish represent adaptations to the specific physical and biological challenges presented by the upstream pathway to a specific spawning area. For example, waterfalls and similar physical barriers may be passable only at a specific range of flows that typically occurs during one month of the year, and then only by fish that have particular physical capabilities for jumping or "scooting" over the barrier. The entire sequence of migration behavior must be properly timed to meet such windows of opportunity. For fall-spawning fish, prevailing warm water conditions in late summer often present strong thermal barriers to movement, and suitable habitats for resting may be few and far between (Berman and Quinn, 1991). Therefore, again at the adult life stage, population-specific behavioral patterns, closely attuned to the mosaic of habitats that is available for migrant adults, may be critical for survival and successful reproduction.

Faithful homing to natal spawning areas is typical, but straying does occur. Adult fish also exhibit a remarkable ability to locate and select high-quality habitat patches for spawning (i.e., areas of suitably sized gravel and cobble with high rates of interstitial flow to modulate temperatures and oxygenate the nest or redd), and they will actively stray from natal habitats to spawn elsewhere when habitat conditions in their stream or reach of origin no longer are suitable or accessible for spawning, or are overcrowded with high densities of spawners.

Once they enter the vicinity of spawning areas, large adult migrant fish can be highly visible and vulnerable to terrestrial (including human) and avian predators. The availability of deep resting pools, riparian forest canopy, undercut banks, and large woody debris accumulations in the proximity of spawning habitats can be critical for survival and successful reproduction of migratory salmonids, particularly those that venture far upstream and that are required to spend long periods holding in small river and stream environments. Cover elements can be particularly important in providing physical shelter from high flow events, or refuge during particularly low flows in spawning areas.

Influence of woody debris on development of high quality habitat

Much of the historical habitat complexity of streams throughout the Columbia Basin was associated with accumulations of large woody debris. Historically, virtually all Columbia Basin streams, including rivers of the high desert, traversed riparian forest mosaics that usually included stands of large-diameter, older trees (Wissmar et al., 1994). These riparian forests (including downed trees in the channel) were often the most accessible source for high-quality logs during settlement and later proliferation of timber markets, so large woody material was eliminated early on, and have subsequently been suppressed by continued logging and grazing in riparian areas (McIntosh et al., 1994; Wissmar et al., 1994). Clearance of rivers to facilitate log drives and other forms of navigation also contributed to loss of natural debris jams in many rivers (Sedell and Froggatt, 1984; 1991)

Large, downed trees and coarse woody debris in the channel and on floodplain surfaces are absolutely integral to the development of habitat in Columbia Basin streams, particularly in the alluvial reaches where substratum size is smaller and interstitial cover more limited than in the boulder-dominated channels of high gradient streams. In concert with the bank stability and flow resistance conferred by living riparian vegetation, coarse woody debris acts to deflect flows, creating low-velocity flow refugia, scouring deep pools, locally trapping sediments and fine organic material that contributes to aquatic food webs, and providing a diverse and stable habitat mosaic used heavily by many kinds of organisms, including salmonid fishes (Sedell and Froggatt, 1984; Naiman, 1992). Debris accumulations may play a direct role in forcing surface flows into alluvial aquifers and promoting efflux of hyporheic flow and shallow groundwater back into surface waters (Ebersole, 1994). At a larger scale, debris jams cause temporary obstructions to the river course that during peak flows promote local channel switching and floodplain inundation, primary processes that create and rejuvenate the diverse mosaic of main channel, backwater, slough, springbrook, and hyporheic habitats common to natural alluvial rivers (Sedell and Froggatt, 1984; Stanford and Ward, 1993). Such channel movement and floodplain inundation also sustains diversity in floodplain vegetative communities. Debris jams may act to divert or break up ice accumulations during winter, preventing the downstream propagation of ice drives that tend to naturally channelize rivers in colder, interior areas (Smith, 1979).

Wood debris likely was a very important feature of the mainstem river as well. Lewis and Clark (Moulton, 1988) noted large jams of huge tree boles in eddies and side channels. Today little or no large woody recruitment is possible, even in the free flowing Hanford Reach, because wood recruitment in tributary rivers is retained in the reservoirs.

Groundwater upwelling: a key attribute of high quality habitat

Large woody debris accumulations and other structures confer to natural alluvial rivers a high degree of morphological complexity that results in highly connected subsurface and surface flow paths. Deep pools, low-velocity backwaters, and springbrooks isolated from main channel flows are common zones of upwelling and concentration of groundwater in ways that create diverse thermal refugia for fishes and other organisms (Sedell et al., 1990; Stanford and Ward, 1993; Ebersole, 1994). These habitats are cold relative to warm surface waters in summer, warmer than surface waters in winter, and can sometimes be nutrient-rich and highly bioproductive (Stanford and Ward, 1993).

In winter, groundwater-influenced stream habitats (upwelling zones in main channels and backwaters; back bar and wall based channels; low-terrace springbrooks), especially on alluvial flood plains, often remain free of anchor and surface ice, buffering them from the stresses of winter freezing and thawing processes that can be highly disruptive of biota, including wintering fishes. Groundwater-influenced habitats are well known to provide important spawning habitats for fall-spawning salmon and bull trout. Historical data are clear on where the fish spawned , e.g., see the maps of Fulton, (1968; 1970) and it is likely that these were areas of groundwater upwelling. Groundwater-rich pools, beaver ponds, and springbrooks also appear to provide critical winter habitat for juvenile and adult salmonids, which may move long distances to congregate in these areas (Cunjak and Power, 1986; Chisolm et al., 1987; Cunjak and Randall, 1993).

In summer, coolwater refugia maintained by groundwater upwelling are known to be used heavily by adult spring chinook (Berman and Quinn, 1991), resident trout (Li et al., 1995) and virtually all other salmonids that inhabit warmer river reaches. In large portions of the Columbia Basin at lower elevations and in desert areas, it is likely that native salmonids would not persist except for the availability of cool refugia at groundwater upwelling sites.

Upwelling areas on alluvial reaches are hot spots of bioproduction because the plant available nutrients accumulate in groundwater flow pathways (Vervier and Naiman, 1992;

Stanford et al., 1994). These nutrients greatly stimulate primary production and likely increase protein content of emergent hydrophytes and riparian woody vegetation. Hence, riverine habitats influenced by ground water provide a more consistent and abundant food supply for all life stages of salmonid fishes and other food web components. This is in contrast to steep gradient canyon segments, where surface and groundwater interactions are limited due to bedrock controls on channel geomorphology. Salmonid habitats are limited to main channel features such as rapids, runs, pools and eddy complexes associated with rock and woody debris.

Complex interactions between ground water and surface water are key attributes of high quality riverine habitat for salmonid fishes in the Columbia River. Since these habitats are created by the inter-relation between flow and bedload movement (cut and fill alluviation) in relation to the slope of the main river channel, these habitats are not distributed uniformly. They are most well developed on aggraded floodplains. Floodplain segments also are human foci within the river continuum, because these tend to be the most productive nodes for agriculture and water diversion and impoundment in the watershed landscapes of the Columbia Basin. As a consequence maintenance of critical salmonid habitat has been problematic owing to conflict of uses. Moreover, owing to the early development of floodplain reaches, salmonid habitat in these areas was compromised to varying extents many years ago and measures to protect rivers have tended to focus on much less productive canyon and high mountain segments that were not only of less importance to humans but also were less important habitats for salmonids in general.

We realize that protection was accorded to various river reaches, not in relation to use by salmonids, but because these segments had wilderness or other values. However, the restoration of habitat complexity in the alluvial reaches should be emphasized in recovery efforts.

CAUSES AND CONSEQUENCES OF HABITAT DEGRADATION

Conclusions from recent reviews and synoptic studies

Vast quantities of information on habitat conditions in Columbia Basin watersheds and streams have been collected by numerous agencies. Unfortunately, the quality and scientific value of much of this information is questionable or very limited, much is inaccessible and perhaps permanently lost, and very little of the remainder that is potentially useful has been comprehensively analyzed, summarized, or otherwise made available in reports or publications. Fortunately, over the past few years, several important reviews and a few comprehensive research studies of salmonid habitat status, trends, and threats in the Pacific Northwest and Columbia Basin have been published. Hence, comprehensive review herein would be redundant; readers are urged to consult the citations given below for details. Our objective in this section is to underscore the general conclusions from these reviews: considerable degradation of salmonid habitat has occurred in the Columbia River Basin; habitat conservation and restoration has not been a priority for management; and, where habitat restoration has been attempted the results generally have been unsuccessful or counterproductive (General Accounting Office, 1992).

Regional reviews of salmonid population status (Nehlsen et al., 1991; Frissell, 1993; Rieman and McIntyre, 1993; Society, 1993; National Research Council, 1995) strongly implicate habitat degradation as a major contributing cause of population decline. Frissell (1993) and The Wilderness Society (1993) point out that regional patterns in decline of salmonids and other fishes in areas not subject to the impacts of dams and major diversions indicate the pervasive importance of general, catchment-wide habitat degradation as a threat to fish populations. This is not to say that construction and operation of the many dams and reservoirs in the Columbia Basin are not important factors in run declines (they are); but, clearly other kinds of human land use and associated freshwater habitat degradation can and do endanger salmonid populations.

General discussions of some mechanisms of habitat change in response to human activities and its effects on riverine ecosystems can be found in Stanford and Ward (1992), Elmore (1992), and Naiman et al. (1992), and in earlier sections of this document. Salo and Cundy (1987), Meehan (1991), Bisson et al. (1993), and FEMAT (Forest Ecosystem Management Assessment Team) (1993) comprehensively review some of the multifarious pathways by which human land management activities are known to degrade habitat and affect salmonid populations. These processes are no different in the Columbia River Basin than elsewhere in the world.

Lichatowich and Mobrand (1995) and (Wissmar et al., 1994) discuss many early references to habitat degradation and its consequences for salmon runs in the Columbia Basin. Many of the historical sources date from prior to the turn of the century, and it is clear that degradation of freshwater habitat (e.g., through intense exploitation of beaver and early mining activity) was well underway in the basin soon after its colonization by Europeans. Available data indicate that coho salmon in the Columbia River Basin were in serious decline by the 1930's, long before construction of mainstem dams began, in part reflecting the effects of extensive human-caused changes in low-elevation habitats (Pacific Rivers Council et al., 1993).

Theurer et al. (1985) developed a modeling procedure to relate riparian vegetation to thermal regimes of streams, and tied this to relationships between temperature and salmon abundance developed in previous Columbia River research. They applied the models to assess fish habitat in the Tucannon River drainage, estimating losses of salmon production caused by riparian land uses in the drainage, and predicting potential gains in salmon populations that might result from protection and restoration of historic levels of riparian forest cover. Though necessarily based on limited data, this work is notably one of the first credible attempts to understand natural Columbia River salmon production and habitat status in the context of large-scale human alteration of ecosystem pattern and process. The results strongly suggest that salmon recovery in the alluvial reaches of the Tucannon and likely in other mid-Columbia rivers (our conclusion) is directly tied to substantial improvements in habitat condition. More recently, Li et al. (1995) reported the results of extensive observational and experimental studies demonstrating impacts on the aquatic system of human disturbances in riparian zones in the John Day Basin, including thermal alteration shown to be highly adverse to salmonid fishes.

Wissmar et al. (1994) and McIntosh et al. (1995; 1995; 1995; 1995; 1995) demonstrate the pervasive, adverse impacts on fish habitat that human activities have caused in the Columbia Basin. They document damaging changes in channel morphology and stability and progressive and persistent loss of riparian vegetation, pools, large wood, and other biologically important habitat elements in streams whose catchments experienced extensive logging, grazing, mining, and other human extractive development. By contrast, streams in catchments dominated by relatively undisrupted wilderness or roadless areas exhibited little long-term change, or even showed improvement in fish habitat conditions over the study period (the past several decades).

Obviously, natural disturbance processes (floods, droughts, diseases) occur episodically in roadless and natural areas, but in general natural disturbances appear to have much less adverse effect on native fishes than do human disturbances. For example, catchments affected by large-scale wildfire since the 1940's, as long as they were not also affected by extensive human activities, appeared to maintain high-quality habitat or improving trends in habitat conditions (1995; 1995; 1995; McIntosh et al., 1995; 1995)

Based on regional assessment of biological and federal-land resources in the Columbia Basin, Henjum et al. (1994) strongly advocated the protection of roadless and late-successional forest lands to provide watershed-level refugia for fishes and other aquatic species. Rhodes et al. (1994) presented extensive synthesis of previously unexamined or fragmentary data from various agency sources to demonstrate the extreme importance of roadless and little-impacted catchments as *de facto* strongholds for declining Snake River salmon. In an analysis of a large field data set on habitat condition and fish populations in the Clearwater River basin in the Upper Columbia, Huntington (1995) showed that roadless catchments, even those that had intensely burned earlier this century, provided higher quality habitat to more diverse and abundant native fish populations than did nearby, heavily "managed" catchments. Huntington's analysis also indicated that non-native species such as the brook trout (*Salvelinus fontinalis*), which can displace native trout and interbreed with bull trout, flourish in catchments where habitats have been more extensively impacted by man. Henjum et al. (1994) and Li et al. (1995) pointed out that even though remaining relatively undisturbed headwater areas may afford marginal habitats relative to the historical distribution of fish species in Oregon, protection of these areas appears critical for near-term persistence and long-term restoration of native fishes, including salmon. In a multi-species biodiversity assessment of the Swan River Basin in Montana, Frissell et al. (1995) found that tributaries draining roadless areas, especially those that have not been extensively stocked with non-native fishes, appeared to be disproportionately important for native trout and other aquatic and wetland-dependent species.

Independent scientific reviews of BPA-funded habitat improvement projects in the Columbia Basin (Beschta et al., 1991; Frissell and Nawa, 1992; Kauffman et al., 1993; Henjum et al., 1994; National Research Council, 1995) have been highly critical of habitat management which has (unsuccessfully) emphasized the installation of costly artificial structures in lieu of full protection and restoration of natural vegetation and ecological processes that create and maintain fish habitat.

Doppelt et al. (1993) offers a lucid critique of misplaced priorities in past policy and habitat management programs, and provides a road map for a more comprehensive and ecologically credible approach to restoration of salmon ecosystems. Their recommendations and Wissmar et al. (1994) suggest that managers focus on identifying existing high-quality watersheds and downstream "nodal" habitats or "hotspots" that are disproportionately important for protecting existing native species populations and protecting them from proposed or recent human disturbances (e.g., through removal of existing logging roads or removal of livestock from riparian areas). Second priority in terms of urgency of action, but equally necessary for long-term success, is restoring adjacent and selected downstream habitat patches than can increase basin-wide biological connectivity and allow expansion, life history diversification, and demographic and genetic re-connection of existing population fragments.

Similar effects from different causes: a brief summary of some pervasive human activities and their consequences on salmonid habitat

A theme of this report is that many kinds of human activities tend to result in similar changes in aquatic ecosystems, although the magnitude, persistence, interactions, and biological outcome of the effects can vary widely according to local conditions and history. While site-specific prediction of impacts can be difficult and uncertain (e.g., influences of a particular forestry prescription; outcome of fish stocking), catchment-scale trends and spatial patterns in freshwater habitat condition in the mainstem Columbia River and its tributaries are generally well documented, predictable and stereotypical (Salo, 1987; Rhodes et al., 1994; Rhodes, 1995). In this section we provide a very general sketch of the typical effects of various human activities in the Columbia Basin.

Beaver trapping

Perhaps the earliest exploitative land use in the Columbia Basin was large-scale trapping of beaver, which began in the mid-1800's (National Research Council, 1995). Beaver dams were historically very extensive in nearly all alluvial and low-gradient segments of Columbia River tributaries, and were common in branches and backwaters of the larger tributaries and Columbia itself. Alluvial flood plains were sites of heavy beaver activity causing streams to meander and braid, thereby maximizing the mosaic structure of salmonid habitats.

Beaver dams and their foraging activities created storage sites that buffered flows of water and downstream transport of organic matter, nutrients, and sediment. Beaver ponds were important rearing and wintering areas for many species of salmonids, and promoted channel switching and geomorphic complexity that encourages extensive exchange of surface and subsurface waters in alluvial aquifers (Naiman and Fetherston, 1993). Another under-appreciated function of the beaver may be its unique role as an upstream vector of vegetative propagules of willow and other important riparian species, allowing their recolonization following debris flows, severe drought, and other catastrophes that can wipe out riparian plant communities in tributary catchments.

Trapping permanently reduced or extirpated most beaver populations, with resulting widespread loss of structural elements, floodplain processes, and vegetative diversity that had developed as a result of centuries of ongoing beaver activity. Throughout the Columbia Basin beaver-mediated creation of salmonid habitat is nowhere near its zenith in the river system that Europeans discovered, even though beaver have been included in state wildlife management programs for at least the latter half of this century.

Logging

Early settlement in the Columbia River basin was concentrated in alluvial bottomlands along lower-elevation tributary rivers and streams, where arable soils and water were plentiful and transportation was most feasible. Logging in floodplains and bottomlands accompanied the earliest settlement for purposes of land clearance, access to and through stream channels for transport, and for construction materials. A sawmill was operating in Vancouver, WA, as early as 1827 (National Research Council, 1995). As regional and national markets and transport systems developed, timber grew rapidly to become a major commercial component of the Pacific Northwest's economy. Cutting of timber remains a widespread industrial activity in the Columbia Basin today, although most large, valuable stands of old-growth forest are long-gone. As shown by Henjum et al. (1994), timber cutting in the Columbia Basin has in many areas been disproportionately concentrated in low-elevation valleys and riparian areas, where high-value species and older trees were historically most abundant.

Logging of trees from riparian areas directly eliminates the source of large woody debris that is so central to many ecosystem processes and the maintenance of habitat complexity and productivity in streams and rivers. Moreover, it directly reduces shade and alters near-surface microclimatic conditions that protect streams from climatically-driven warming in summer and freezing in winter (Salo, 1987; Maser, 1988; FEMAT (Forest Ecosystem Management Assessment Team), 1993; Naiman and Fetherston, 1993). Removal of standing live trees or downed wood can jeopardize the long-term stability of channel banks, floodplain, and toeslope surfaces. In areas where tree regeneration is dependent on seed sources or specific ecological conditions, logging has resulted in the permanent loss of ecologically valuable tree species such as western red cedar and ponderosa pine. In addition, operation of machinery necessary to cut and remove trees can directly damage soils, vegetation, and channel feature, altering ecological processes in these sensitive areas.

Despite speculation to the contrary, no study has demonstrated that "safe" or "beneficial" levels or methods of logging in riparian and floodplain areas exist from the standpoint of maintaining the many natural ecological functions of forests. This is exacerbated by the massive, regional scale at which previous logging has caused long-term impoverishment or impairment of ecological components and processes in the Columbia Basin. Therefore recent scientific assessments have recommended no removal of trees from these key areas (FEMAT (Forest Ecosystem Management Assessment Team), 1993; Henjum et al., 1994; Rhodes et al., 1994).

Although today the logging of riparian and floodplain forests continues in many areas, most timber harvest volume is produced by more extensive and frequent cutting of smaller, lower-value trees over larger, upland areas, which requires extensive road networks and results in major alteration of forest cover conditions across large catchments. These landscape alterations have different, but equally threatening effects on catchment processes and freshwater habitat.

Although humans build roads for many purposes, the vast majority of roads in the Columbia Basin have been (and continue to be) constructed for purposes of logging transport and access for silvicultural management of commercial forest lands. In the spectrum of natural disturbance processes, road networks have no known natural analogue. Road networks are direct sources of accelerated sediment production and efficient delivery to the stream network (Meehan, 1991; Rhodes et al., 1994). Roads also permanently intercept and re-direct surface and subsurface flow of water, altering hydrologic and thermal regimes in streams (Meehan, 1991; Rhodes et al., 1994). Roads can serve as vectors for forest pathogens and increase the spatial extent of a wide range of human activities, such as legal fishing, poaching, and deliberate or unintentional introduction of non-native species that threaten native biodiversity (Frissell and Adams, 1995; Frissell et al., 1995; Noss and Murphy, 1995).

Logging often results in the removal of forest cover in patterns and at rates far exceeding the scope of natural events that have historically dominated forest landscapes in the Columbia Basin. Moreover, unlike fire, disease, windthrow, and other natural forest disturbances, logging causes the large-scale removal of largest size fractions of woody debris from forests (Maser, 1988). The mechanical means used for cutting and removing large trees can create unnatural soil disturbance and compaction that accelerates surface erosion and alters hydrologic relations Opening the forest canopy, especially if it occurs across a significant portion of a catchment, alters microclimate, snow accumulation and melt and other aspects of precipitation, and can change the routing and slope storage of water, often resulting in downstream changes in streamflow and channel stability that are detrimental to fishes. Such changes typically include increased flashiness of discharge, increased peak flows, and accompanying increases in sediment load due to erosion of channel margins and heads. On steep and unstable terrain, changes in subsurface flows and soil moisture, perhaps together with reduced root strength, can increase the frequency and alter the style of landslide and gully erosion (Salo, 1987; Meehan, 1991; Naiman and Fetherston, 1993; Rhodes et al., 1994). Increased transpiration and reduced moisture-capturing and retaining efficiency of second-growth forests following extensive logging can result in long-term depletion of summer and fall low steam flows, even as winter and spring peak flows increase (Hicks et al., 1991; Rhodes et al., 1994). Despite the vast spatial extent of past and present logging activities in the Columbia Basin, few of these ecosystem changes are satisfactorily explained or accounted for in existing models of cumulative watershed effects employed by land management agencies to assess environmental impacts, and these processes are rarely monitored on a site-specific or watershed basis.

Grazing

Grazing by domestic livestock can change riparian and stream channel characteristics that are detrimental to salmonids. Kauffman and Krueger (1984), Platts (1991), and Rhodes et al. (1994) provide valuable reviews of this subject. While grazing by domestic species began very early in some areas with cultivation of horse herds by Indian tribes (e.g., the Grande Ronde basin), large numbers of sheep and cattle arrived with European settlers during the late 1800's. Even though peak numbers of livestock probably occurred prior to the turn of the century, grazing impacts on aquatic systems since then have continued relatively unabated. More than a century of continuous grazing in many areas has caused progressive deterioration of range and riparian conditions throughout the Columbia Basin (Rhodes et al., 1994; Wissmar et al., 1994; Lichatowich and Mobrand, 1995).

Livestock impacts to streams occur through three major vectors: 1) direct trampling of channels, banks, and soils; 2) removal and alteration of vegetation, particularly in riparian areas;

and 3) direct introduction or overland flow of fecal wastes and urine into surface waters. The direct effects of large, grazing animals include trampling and sloughing of streambanks, loss of overhanging banks, accelerated bank erosion, compaction of soils and increased sediment input to adjacent and downstream reaches. Grazing and trampling of vegetation in riparian areas and floodplains generally reduces vegetative cover and vigor, suppresses or eliminates some vegetation species (especially palatable but ecologically critical woody species such as willows), and reduces canopy cover over the channel. The result is typically widened and open channels, with lower, warmer, more turbid surface flows in summer, more extensive and damaging ice conditions in winter, and flashier, more turbid, flows in winter and spring runoff periods. Fine sediment concentrations increase and channel stability decreases (Meehan, 1991; Rhodes et al., 1994; Li et al., 1995). Eutrophic enrichment from livestock wastes can cause depletion of oxygen required by fishes and their principle food organisms. These changes are adverse to salmonids at virtually all life stages.

Mining

The many effects of mining are discussed in general terms in Nelson et al. (Meehan, 1991, in Chapter 12). Although extensive mining has occurred in many areas of the Columbia River basin, the history and effects of these activities have not been comprehensively compiled and described in any single source. Mining effects, although difficult to sort out from those of many other simultaneous and subsequent disturbances, were no doubt extensive in some major tributaries (e.g., John Day River, Salmon River, Coeur d'Alene River, Upper Clark Fork River) by the late 1800's. It is likely that the historic impacts of mining on salmon and native trout have been given short shrift in recent reviews (National Research Council, 1995) because of the relative paucity of information, and perhaps because mining today is less widespread an activity than logging, grazing, and irrigated and cropland agriculture. However, the old disturbances and their effects remain.

Mining activities of various kind inflict intense soil disturbance and erosion. In addition to very large sediment inputs to downstream reaches, placer mining causes direct, wholesale destruction of natural channels, floodplains, valley floor soils and vegetation, and alluvial aquifers. Natural recovery is inhibited, perhaps permanently. Areas of the Upper Grande Ronde basin (McIntosh et al., 1994) and elsewhere subjected to placer mining, for example, have not recovered to any semblance of natural structure and function in more than a century. Leaching of toxic materials from mining wastes and milling sites can permanently contaminate and impair the productivity of stream and riverine ecosystems many kilometers downstream, as is most evident in the Upper Clark Fork and Coeur d'Alene river basins in the headwaters of the Columbia, where native salmonids have been virtually eliminated from the affected waters for a century or longer.

It appears likely that other mining districts may suffer more subtle, not yet documented depressions in biological productivity from mining waste toxicity.

Irrigation and cropland agriculture

Cropland agriculture affects vast areas of the Columbia River Basin, although this activity is perhaps most concentrated on arid basalt plateaus and Palouse prairie country where surface waters are scarce. No comprehensive review of the effects of cropland agriculture on fish habitat in the Columbia Basin exists, as far as we know. Farming can significantly alter hydrology and increases erosion and sedimentation processes many-fold over natural rates. Where farming impinges on wetlands, floodplains, and riparian areas, it directly destroys riparian vegetation and channel structure. The principal effects of cropland agriculture on fish in the Columbia Basin no doubt stem from flow diversion and withdrawal for irrigation (National Research Council, 1995). Some irrigation also occurs to support grazing of pasture. Irrigated agriculture began with early settlement in the mid-1800's, but rapidly accelerated with the assistance of large, government-subsidized projects starting in the early 1900's and continuing to the present.

Although a widespread problem globally, few good review papers are available that address the scope of activities and effects of irrigation on freshwater habitat and fish populations. There has not been a comprehensive ecological assessment of the consequences of irrigation for fish in the Columbia Basin.

Dams and diversions for to provide water for irrigation can block movements of migratory fishes and divert fish from natural habitats into ditches or onto fields, killing them. Diversions de-water natural habitats, reducing habitat available in streams and sometimes rendering it entirely hostile (e.g., through warming) or a barrier to fish passage (e.g., loss of surface flow through riffle crests). Water in storage ponds typically warms much more than water free-flowing in streams and natural aquifers. Water that is returned to streams from irrigated fields is typically warm and often laden with very high concentrations of sediments, nutrients, and pesticides. Vaccaro (1988) developed a simulation model of the effects of irrigation diversions on surface water temperature in the Yakima River Basin. Vaccaro projected that removing the effects of irrigation diversion could cool summertime temperatures in critical salmon habitats by up to 2°C; this effect was most pronounced at lower elevations where larger, alluvial reaches of the river and its tributaries once supported abundant salmon production (Lichatowich and Mobrand, 1995).

Urban and other sources of excessive nutrients and toxic pollutants

Concentrations of dissolved solids and pollutant loads generally increase from headwaters to oceanic confluence in most of the nation's large rivers, including the Snake and Columbia Rivers (Smith et al., 1987) as a consequence of the cumulative loads of pollutants from all land use activities. A primary source is treated sewage effluents and storm drainage from the urban areas along the river corridors. Oxygen depletions and other indicators of severe organic and nutrient pollution from point sources near and within urban centers were once common in the lower mainstem reaches of the Columbia River and many of the larger tributaries (Stober and Nakatani, 1992). Owing to the Federal Clean Water Act, sewage treatment, including effluents from pulp mills and other industrial sources, have been substantially improved in the last two decades. Creation of many reservoirs within the continuum also contributed to the decline in pollution because they are processed by food webs and retained in reservoir sediments. However, continuing concern exists for loading of plant growth nutrients in the large on-channel lakes and reservoirs and loads are being legally allocated to sources through actions to limit the total maximum daily load to lakes, e.g., Flathead (MT) (Flathead Basin Commission, 1994) and Long (WA) (Sotero et al., 1992) Lakes. Moreover, metals and organic carcinogens are present in fish tissues throughout the Basin (Stober and Nakatani, 1992), even in headwater systems like Flathead Lake (detectable PCB concentrations in fish tissues) (Flathead Basin Commission, 1994) underscoring the need for continued vigilance. Damkaer and Dey (1986) found that fluoride effluent from the aluminum plant upstream from John Day Dam caused delays of as much as 4 days in passage of chinook past John Day Dam.

Nonetheless, water pollutants, other than from fine sediments, increased temperature and metals from mining districts as discussed elsewhere in this report, generally are not considered a major factor in salmonid declines nor particularly problematic for recovery (see discussion of temperature effects below). We are not sure that the available data have been examined well enough to agree with this consensus. Indeed, data on pollution loads, particularly from diffuse (non-point) sources and interactions between maintenance of salmonid critical habitats for all life stages has not been examined extensively in the Columbia River system, at least in the context of salmonid restoration.

Stream regulation: effects of dams, reservoirs and diversions

Flow regulation for purposes of hydropower production and flood control has been the primary issue for salmonid conservation and restoration in the Columbia Basin, since construction of the first small tributary dams for power generation early this century. The effects of dams in the basin were magnified by construction of mainstem projects since 1938 that directly affect virtually all migratory fishes in the middle and upper Columbia Basin.

Mortality of salmonid fishes caused by dam passage (e.g., through turbines and bypass facilities) has dominated discussion and actions for salmonid recovery. Many millions of dollars have been spent on facilities and research to increase bypass efficiency in the absence of accurate mortality estimation. Recent studies on the Snake River suggest far lower mortality associated with reservoir transit and dam bypass by wild fall chinook than previously thought. These issues are discussed in detail elsewhere in this report. We note that recovery efforts also have focused heavily on decreasing the transit time for smolts in the highly regulated mainstem either by use of storage releases to move smolts out of the system or by barging, even though such actions clearly are selective of specific life history types. We conclude that greater attention to habitat related effects of stream regulation is needed.

The ecology of regulated streams has been summarized in several volumes (Ward and Stanford, 1979; Lillehammer and Saltveit, 1984; Lillehammer, 1984; Craig and Kemper, 1987; Petts and Wood, 1988; Petts et al., 1989; Calow and Petts, 1992; Hauer, 1993). Principles from a very diverse and detailed literature (Stanford et al., *in press*) directly apply to the Columbia River. In this section we point out that dams have many important consequences for salmonid habitat and populations, including: 1) destruction of riverine habitat upstream of dams and its conversion to novel, reservoir habitats; and, 2) the creation of highly artificial flow, thermal, and sediment regimes downstream of dams.

Reservoirs represent massive loss of the once-highly-productive riverine habitat that occurred above most dam sites. Optimal dam sites are often located at narrow bedrock constrictions below wide, aggraded valleys, which allow large storage ratios for a given dam size. As described above, these aggraded, alluvial reaches correspond to highly productive riverine habitats for fishes and other native biota, where lateral habitat complexity is high, interaction between groundwater and surface waters is great, and natural riparian vegetation is extensive, heterogeneous, and productive (Stanford and Ward, 1993, Naiman, 1993 #16284). Not only was key habitat lost to inundation, flow regulation has vastly changed riverine habitats downstream. Operation of the dams limits peak flows and increases baseflow causing channels to degrade and disconnect from floodplains and channel substratum to armor with large rocks and cobbles. Even in the relatively constricted mainstem Columbia River alluvial features prevailed in the form of complex island, point and eddy reattachment bars composed of sand, gravel and cobble. Back bar channels and sloughs were common features of the mainstem channels and floodplains. All of the mainstem habitat open to anadromous fishes above Bonneville Dam is now lacustrine (Figure 5.1), except for the Hanford Reach. However, bars in the Hanford Reach are composed of very large cobble, the fines having been sluiced out, and back bar channels and sloughs are largely filled in with riparian vegetation owing to years of rapidly fluctuating base flow and lack of peak flows.

Native salmonids clearly exploited these lost alluvial habitats heavily as spawning, nursery, refuge, and resting areas based on early inventories of salmonid habitat (Fulton, 1968; Fulton, 1970) Migratory salmon that originated all over the upper Columbia passed through these river segments as juveniles and adults, and these fish almost certainly took advantage of such riverine habitats to varying degrees. It is unknown to what extent reservoirs replace the ecological functions of these lost riverine habitats, but the status and trend of many fish populations suggests to a large degree they do not (Lichatowich and Mobrand, 1995).

Reservoir storage and dam operations dramatically alter flow regimes of rivers downstream of the projects as well. Typically, natural seasonal flow peaks are reduced and delayed or eliminated, and low flow periods are continuously or intermittently augmented by controlled releases. These changes in hydrology, coupled with the effects of limnetic processes (e.g., seasonal, vertical stratification of temperature and biotic productivity) that affect reservoir water before its release, substantially alter thermal and nutrient regimes, which are typically highly predictable in natural, free-flowing large rivers of the Columbia Basin (Stanford and Hauer, 1992; Brusven et al., 1995). As a consequence, high quality rearing habitat associated with shallow low-velocity floodplain features become progressively disconnected from the channel. Owing to lack of scour associated with flooding, these key habitats fill with sediments and dense vegetation. In many cases the vegetation is non-native and regulated streams are active corridors for spread of noxious weeds and woody plants. Indeed, an axiom of the ecology of regulated streams is that artificial regulation of flow, temperature and nutrients favors a select few species, often non-native ones, over the majority of native species whose life histories are evolutionarily adapted to the naturally prevailing thermal and hydrologic template. Accompanying these flow alterations are changes in turbidity and sediment transport caused by storage of sediments behind the dam or lack of scour to move fine sediments influent below the dams, which also can stress native fishes and their natural prey base by altering riverine habitat dynamics and reducing habitat diversity. Moreover, short term baseflow fluctuations associated with hydropower peaking operations produce a large zone along each side of the river where aquatic biota cannot live. This so-called varial zone, which includes all of the shallow, low-velocity habitats within the river channel, occurs on all regulated river segments in the Columbia Basin and substantially compromises instream food webs and productivity. Juvenile salmonids cannot feed and rest in fluctuating flows and are washed downstream whether they want to or not (see Chapter 6 below). Moreover, shallow-water food supplies for juveniles is limited or non-existent.

Stanford et al. (*in press*) proposed a protocol for restoring these lost functions to regulated rivers. They proposed that channel-floodplain connectivity and revitalization of instream habitat structures can be accomplished by re-regulation of flows and temperatures (e.g., by selective release structures) to more normative regimes, assuming that temperature (see below) or pollution are not also a problem. Scouring flows are possible in most regulated reaches on at least average to wet years. Reduction of base flow fluctuation to normative conditions can be accomplished by base loading the turbines; to reduce revenue lost from loss of peaking capability, base flows may be higher than historically occurred but they cannot be fluctuated if a productive food web is to develop in the varial zone. In the Columbia River system, revenue lost by base loading some dams perhaps could be offset by peaking other dams that do not have riverine segments downstream (e.g., the mid-Columbia dams could be operated as reregulation systems for Grand Coulee peaking operations). Moreover, peaking flows provide turbulent waves that likely assist movement of juvenile salmonids through reservoir-dominated reaches (see Chapter 6. below). Obviously, reregulating the Columbia River system in a more normative fashion requires careful analysis. This was attempted in the recently completed System Operations Review; however, the analysis itself and none of the alternatives embraced the principles of the ecology of regulated streams in the manner discussed here.

All of these principles apply equally well to the many regulated tributaries of the mainstem Columbia River. Establishment of normative flow and temperature conditions is possible in many tributaries by reregulation of discharge schedules from the storage reservoirs in the headwaters. Rivers such as the Yakama, Walla Walla and Umatilla are heavily impacted by irrigation withdrawals and high temperatures during periods of very low baseflows. These flows are far less than normative. Indeed, some segments are dry part of the time. Salmon and other aquatic biota cannot exist in these key tributaries in any sustainable numbers until baseflows are elevated to a stage that allows productive food webs to persist in channel and shallow floodplain habitats. Higher base flows will also allow effective interstitial flow through gravel bars and floodplains which likely will substantially cool surface waters in upwelling zones during critical late summer hot periods

Watershed as the Management Unit

It is well-established in the scientific literature that the land and aquatic area comprising watershed or catchment basin exerts strong physical and biological controls on the development of stream and lake ecosystems, e.g., (Schumm and Lichty, 1956; Hynes, 1975; Frissell et al., 1986; Sheldon, 1988; Moyle and Sato, 1991; Stanford et al., *in press*). In the past, attempts to protect and restore aquatic habitat and populations have often met with failure because they disregarded the overriding role of catchment conditions and processes in shaping aquatic ecosystems (Platts and Nelson, 1985; Frissell and Nawa, 1992; Doppelt et al., 1993; Rhodes et al., 1994; Sear, 1994).

Non-native fishes

The Columbia River ecosystem is home to many species of native and non-native fishes (Table 5.2). In general native fishes have declined in range and abundance while non-natives have proliferated.

As has been emphasized in previous sections of this report, through homing and natural selection each native salmonid population is closely adapted to the particular array of habitats that is available to it. Non-native fishes have been widely introduced in the Columbia Basin (see Table 5.3), but it is notable that introduced fishes tend to be most successful in streams and rivers where natural habitat has been altered and native fishes depleted. Large-scale human disruption of historic habitat mosaics can create novel ecological niches that native fishes have not evolved to fill, providing a toehold for the invasion and eventual proliferation of introduced species (Balz and Moyle, 1993). For example, Huntington (1995) reported that non-native brook trout were more abundant in streams draining extensively logged areas of the Clearwater National Forest in Idaho than in streams whose catchments were predominantly roadless and unlogged. The presence of the brook trout may have been due to easier access afforded by roading which likely facilitated planting of brook trout as well as increased fishing pressure on the natives. The logging itself may have been only indirectly involved as related to habitat modification associated with increased water and sediment yield.

Direct human alteration of riverine ecosystems in the Columbia Basin has massively promoted the proliferation of non-native fish species. Li et al. (1987) documented fish assemblage structure in major reaches of the mainstem Columbia, and found that all reservoirs were strongly dominated by non-native species such as smallmouth bass, walleye, yellow perch, and channel catfish. Most of these species are voracious predators on other fishes, and many are known to consume young salmon. These species also tend to prefer different thermal conditions than do native salmonids, so that they may be favored by the many human activities that alter thermal regimes.

By contrast while the free-flowing Hanford reach of the Columbia includes small numbers of virtually all the same species, its overall fish numbers and biomass remain dominated by salmonids and other native fish species (Li et al., 1987). This is strong evidence that maintaining (or restoring) a semblance of historical seasonal flow regime can benefit native fishes and select against introduced species that prey on or otherwise adversely interact with salmon and other native species.

Recent evidence suggests that proliferating non-native fishes in mainstem reservoirs could serve as source populations that promote the progressive invasion of tributary streams (J. Ebersole, C. Frissell, and W. Liss, unpublished data, Oregon State University). This could complicate proposals for restoration, if flow augmentation, drawdowns, and other schemes that strongly affect reservoir levels result in displacement or emigration of large numbers of non-native fishes from mainstem habitats into tributary streams. The result could be temporarily if not permanently increased interaction between wild salmonids and non-native fishes in tributary environments that have so far remained mostly free of dominance by non-native fishes. Continued degradation of habitats in tributary streams and possible climate changes also promote the possibility of wider invasion and establishment of non-native, warmwater and coolwater fishes in the basin.

Changed Food Production in the Mainstem

Juvenile salmonids use the mainstems of the Columbia and Snake rivers both as migration corridors and as habitats for feeding. How well we understand feeding (and resulting growth) may be as important as how well we understand migration. The feeding function is especially important for underyearling fall chinook salmon, which grow as they slowly migrate downstream (see Chapter 6). Yearling salmon and steelhead also feed during migration, as documented in Chapter 6, although their transit of the mainstem is more rapid. The Columbia River basin mainstem, however, has changed greatly in recent years and appears to have lost a major portion of its normal, riverine carrying capacity for feeding juvenile salmonids, particularly outmigrants. This review has looked carefully at components of that capacity that must have been present in the early historical river before about the 1930's and compared them with the present altered (dammed and flow-regulated) condition in the template-patient fashion of Lichatowich et al., (1995). Clearly, the food-producing and feeding habitats of the mainstem Snake and Columbia rivers differ considerably today from those that shaped the evolution of anadromous salmonids. Some alternative foods more typical of slower water have replaced the normal riverine food chain, with unresolved questions of the adequacy of that replacement for feeding migrating salmonids. With a feeding habitat greatly changed and probably much depleted, release of large numbers of hatchery fish into it may exacerbate an already tenuous situation for wild stocks.

The Riverine Food Web

Juvenile salmonids in a riverine environment feed primarily on drifting aquatic insects and terrestrial insects that fall into the water. For smaller salmonids, midges (chironomids) are the predominant source; as fish grow, they eat more of the larger aquatic insects such as caddisflies and mayflies. For example, chironomids and other aquatic insects were highlighted by the earliest studies of chinook salmon in the Columbia River (Chapman and Quistorff 1938). Coho salmon fry in British Columbia were shown to eat pupae, adults, and pupal exuviae (shed skins) of chironomids as they drift downstream (Mundie, 1971). Becker (1973) established that newly-emerged adult midges composed more than half of the diet of underyearling chinook salmon in the

Hanford reach of the Columbia River. Dauble et al. (1980) found midge larvae and pupae accounted for 78 percent by number and 59 percent by volume of the total ingested items in the Hanford Reach. Caddisfly adults became more important as food items there in June and July, as did shallow-water cladocerans (*Daphnia*). Loftus and Lenon (1977) found chironomids were the most important food for chinook salmon in an Alaska river and that heavy feeding occurred during downstream migration. In the lower Columbia River below Bonneville Dam, Craddock et al. (1976) found insects, both adult and larvae, to be the dominant food in spring and fall, although zooplankton from upstream reservoirs was important in summer. In New Zealand, Sagar and Glova (1987) found introduced chinook salmon eating drifting chironomid larvae and pupae, and mayflies in spring and more terrestrial insects in summer. Some other studies in small streams have shown young chinook salmon to eat mostly drifting terrestrial insects (Johnson 1981; Sagar and Eldon 1983). Rondorf et al. (1990) found caddis flies to be the main food item for subyearling chinook salmon (64 percent by weight) in the lower Hanford Reach in May to August. There is less information for yearling salmon, but Schreck et al. (1995) found a wide range of aquatic and terrestrial insects in mostly full stomachs of yearling chinook salmon in the free-flowing Willamette River, with diptera (including chironomids) being either the principal or an abundant component. Rondorf et al. (1985) considered migrating smolts to be actively feeding to offset the depletion of energy reserves during seaward migration. Kolok and Rondorf (1987) reported on food components of juvenile spring chinook salmon in John Day Reservoir. Thus, the general food and feeding relationships of young salmonids in rivers seem well established, although more information could be useful for yearlings.

Riverine environments tend to produce aquatic insects adapted to flowing waters while terrestrial insects fall to the water from the riparian zone. The predam mainstem Columbia and Snake Rivers were classic gravel-bed rivers, dominated by gravel and cobble (rounded rock) substratum variously constituted as bars, low islands, runs and pools with backchannels and sloughs. These are the habitats that produce large numbers of aquatic insects. Alluvial gravel reaches alternated with more canyon-like reaches where bedrock was exposed. Riparian vegetation was typically restricted to a narrow shoreline zone in the upper arid region that constitutes much of the migration corridor (Buss and Wing 1966; Hanson and Eberhardt 1971; Lewke and Buss 1977; Fickeisen et al. 1980a, b; Rickard, 1982). Different floral communities colonized shifting sands at the river's edge, alluvial fans at the mouths of tributary canyons, cobble and gravel slopes, outcroppings of basalt and granite, and disturbed areas caused by annual erosion, rock slides, grazing, and flooding that resulted in seral plant stages. In the entire mainstem, these features remain only in the Hanford reach of the mid-Columbia and transition zones of the lower reaches of the Clearwater River and the Snake River below Hells Canyon Dam to the upper reaches of the Lower Granite pool.

The salmonid life cycles were intimately linked to an annual flooding cycle of the mainstem. Although it is widely understood that juvenile migrants use the spring freshet for downstream migration, it is less well recognized that feeding is also aided by flooding. Fall chinook salmon fry emerging from gravels in spring typically began their feeding and rearing phase in shorelines and sloughs as mainstem water levels rose across cobble bars and into riparian vegetation with the melt of winter snowpacks in the tributaries. The most active rearing period for chinook underyearlings in the mainstem often occurred in late spring and early summer when waters were highest and the most riparian vegetation was flooded. The underyearlings moved gradually downstream through the summer, rearing as they went. Yearlings moved downstream relatively quickly during this same spring freshet period, but there is evidence that they, too, paused periodically in backeddies to feed (Schreck et al., 1995).

Submerged riparian vegetation was probably important for young salmon as a substrate for production of invertebrate food, although this has not been shown directly for the mainstem Columbia and Snake rivers. There is ample evidence from other scientific studies that submerged plant material may be related generally to prey abundance and fish growth. Submerged wood is clearly an important habitat in other aquatic systems for growing invertebrates, especially aquatic insects such as chironomids (midges) (Nilsen and Larimore, 1973, Benke, 1984 #542, Stites, 1989 #13326). More abundant submerged surfaces generally translate to more invertebrates, as with submerged stream macrophytes (Gregg and Rose, 1985).

Flooding provides not only surface areas for aquatic insects but also the colonizers. Larval chironomids of all sizes are a common component of stream drift (Mundie, 1971), especially during periods of flooding. Although larvae are not commonly eaten by young salmon, drift of chironomid larvae seems to serve largely to colonize the submerged gravel and plant surfaces, where the larvae feed on periphyton and attached organic silt and grow rapidly (Oliver 1971). Drifting chironomid larvae loosened from the streambed or as newly hatched instars quickly colonize previously exposed cobbles and submerged vegetation when waters rise. They develop within a few weeks to the pupae and emerging adults that are the preferred food for young salmonids (many chironomid species have short generation times and very high annual productivity). Timing was probably important for feeding salmon: chironomids have their normal peak of production in the spring at the time of peak abundance of downstream-migrating juvenile salmon.

The flooded riparian vegetation also provides terrestrial insects (e.g., ants and spiders) used as salmon food. Because young salmon are at the edges of rivers (underyearlings) and in backeddies (yearlings), they are away from most of the drifting benthic (lithic) invertebrates and in a zone where aquatic and terrestrial drift derived from overhanging brush and flooded riparian vegetation would be most valuable to them. The importance of flood pulses in riverine ecosystems in general is becoming more recognized and is described by Power et al. (1988), Welcomme (1988) and Junk et al. (1989).

Historically positive flow-survival relationships for salmon in the Columbia-Snake rivers may relate, at least in part, to the amount of riparian vegetation flooded during high-flow years. More flooding, when it occurred in a high-volume peak that lasted several weeks as in the mid-Columbia in 1965, would make a large amount of riparian substrates available for aquatic insect colonization and production of abundant food. This hypothesis has not been tested, and may be impossible to test because of other flow-related phenomena that occur simultaneously.

Hydrosystem alterations of food webs

The result of mainstem impoundment and flow regulation is a mainstem ecosystem that does not appear capable of producing nearly as much high-quality food for juvenile salmon as did the free-flowing and annually flooding river. The success of fall chinook salmon in the still-riverine Hanford reach compared to the endangered status of this race in the fully dammed lower Snake River is perhaps partly a result of the differences in food production in the rearing-migration corridor. Research has identified physical and biological causes for the decline and change in food availability.

a) Loss of riverine insect production.

Hydroelectric development has transformed riverine reaches into reservoirs with slow currents, silt bottoms, and fairly stable water elevations. River-like conditions exist in dam tailwaters and persist for a few miles into each reservoir, but most riverine habitat has been lost. With loss of flowing-water habitat has gone the hard-substrate community of chironomids, caddisflies, mayflies, and other insects that fed juvenile salmon (the riverine food chain). In its place have come midges characteristic of soft substrates and aquatic worms, with planktonic zooplankton becoming a major replacement food (Bennett et al. 1988, 1993). Slowly moving shoreline waters of reservoirs warm rapidly in summer, forcing juvenile salmon to move out of their normal shoreline habitat and to the cooler channel (Curet, 1993). Fish that relied on shoreline-oriented food production are now obliged to feed on reservoir zooplankton (Muir and Emmett, 1988, Rondorf, 1990 #18399). D. Bennett and his students at the University of Idaho have recently attempted to quantify the changes in bottom fauna.

b) Loss of riparian flooding.

Impoundment and flow regulation by upstream reservoirs have reduced historical flood pulses that previously had inundated vegetated shoreline areas and produced abundant food for salmon. Shorelines once fringed with vegetation are now lined with rock riprap (U.S. Army

Corps of Engineers 1976), which produces little insect life suitable as salmonid food (Janecek and Moog, 1994). Other shorelines are eroding banks. Even where riparian vegetation has developed as reservoir shorelines age, the stability of reservoir surface elevations during salmon outmigration prevents significant flooding and food production.

Current knowledge specific to the Columbia and Snake rivers falls short of quantifying the benefit of flooded riparian vegetation in the normative ecology of juvenile salmon (although research is still possible at Hanford) and its loss through most of the mainstem. Such knowledge would, however, be useful for the contemporary problem of rehabilitating the carrying capacity of salmon rearing habitats. The reasonable, but locally undemonstrated, importance of riparian habitat for invertebrate (especially chironomid) food production could be a working hypothesis for studies of carrying capacity in the Columbia River basin mainstem rivers and lower tributaries. Useful comparisons could be made between Hanford and various reservoir reaches to quantify, as best we can today, the losses through impoundment. If the hypothesized benefits are substantiated and high, then proposals for flow augmentation and reservoir drawdowns could logically take into consideration a restoration of more natural shoreline vegetation and its seasonal flooding.

c) Altered timing of production and consumption.

Hydropower development has apparently altered the match in timing between food production and demand. Whereas much attention has been given to timing of juvenile outmigrations to match food-production cycles in the estuary and ocean, the "window of opportunity" (Walters et al., 1978), little attention has been paid to correlations between timing of fish abundance, flooding of riparian habitats, and alternative food-production cycles in the mainstem. Evidence suggests that the reservoir zooplankton on which salmon now feed develops primarily later in summer. This topic needs more research and analysis.

d) Invasion of reservoirs by estuarine invertebrate species.

Mainstem reservoirs have been colonized by invertebrate species usually associated with estuaries, and one of these species (*Corophium salmonis*) has become a prominent part of the salmonid food chain in lower Columbia River reservoirs. In the lower mainstem, *Corophium* has become the predominant food for downstream migrants (Muir and Emmett, 1988). *Corophium* now occurs to the headwaters of Lower Granite Reservoir, where it was the most prevalent invertebrate species in both numbers and biomass between August 1993 and September 1995 (Nightengale and Bennett 1996). It does not appear to be eaten by juvenile salmonids there, however. Another estuarine species, *Neomysis mercedis*, has also become abundant in the mainstem, but its direct and indirect effects on feeding are not known. *Mysis relicta* introduced to freshwater lakes such as Flathead Lake, Montana, has caused much ecological havoc, including detrimental competition with kokanee for planktonic food (Spencer et al., 1991). An "estuarinization" of the mainstem Columbia and Snake rivers has apparently taken place, which may be related to the current poor strength of salmonid populations.

Estuarine species now in the mainstem Columbia are native to the upper Columbia River estuary. Haertel and Osterberg (1967), in their comprehensive, integrated study of the Columbia River estuary, described the sediment-surface invertebrate community as dominated by the crustacean *Neomysis mercedis* with high numerical abundance of several species of the gammarid amphipod *Corophium*. More recent studies of the estuary by Simenstad and Cordell (1985) and Jones et al. (1990) showed *Corophium salmonis* occurred abundantly in the epibenthos in shallow tidal flat and deeper slope habitats of the upper estuary during the early spring fluctuating-flow season. As the high flow season progressed, *Neomysis* became dominant. *Corophium*, especially, is a major food item for salmonids in Northwest estuaries, Columbia (McCabe et al. 1983), Sacramento-San Joaquin, California (Sasaki 1966), Sixes River, Oregon (Reimers et al. 1978), Grays Harbor, Washington (Herrmann 1971), Duwamish estuary, Washington (Meyer, 1981).

In 1984, *Corophium* dominated the food of juvenile salmonids migrating downstream through Bonneville Dam (Muir and Emmett, 1988). This estuarine species was being eaten in the fully freshwater Bonneville Reservoir. There was heavy use of these amphipods by all species of salmon. During the spring migration, Corophium constituted 99 percent of the diet of steelhead, 87 percent in sockeye salmon, 94 percent in coho, 97 percent in yearling chinook salmon, and 90 percent in subyearling chinook salmon. During summer (July and August), the importance of *Corophium* declined dramatically and was replaced by the freshwater plankter Daphnia and adult chironomids. High availability of Corophium was believed to be the main factor in food selection, as all species ate *Corophium* in the same time period.

Muir and Emmett (1988) discussed why salmonid juveniles with a preference for suspended, moving organisms would feed on a tube-dwelling benthic invertebrate. *Corophium salmonis* undergoes vertical migrations in the estuarine water column, both daily and seasonally, with migrational peaks occurring in the evening hours and during spring months (Davis, 1978), Wilson 1983). These migrations, coupled with higher flows during spring, were thought to keep these amphipods suspended in the water for long enough periods of time for them to be susceptible to predation by salmonids. *Corophium* availability thus seems to peak in spring during the major salmonid outmigration and to coincide with peak feeding times (evening) of juvenile salmonids (Johnson 1981; Rondorf et al 1985). Although this behavior was not substantiated for the Bonneville pool, it is consistent with stomach content observations at Bonneville Dam. Nightengale (personal communication) indicated that the *Corophium* in Lower Granite Reservoir does not appear to undergo this vertical migration and is not a major food item for salmonids there.

Corophium had expanded its distribution upriver into the John Day pool by 1982, as evidenced by its presence in juvenile spring chinook salmon stomachs (Kolok and Rondorf 1987). Although terrestrial insects and chironomids were eaten most at the site at River Kilometer 395, *Corophium* accounted for 0.8 to 11 percent of the stomach contents. *Neomysis* was observed by ISG members in smolt monitoring station holding tanks in the lower Columbia River in 1994, but its presence has not been studied as it has not apparently been eaten by salmonids.

Neomysis presence and effects are little known. They were not in the food of juvenile salmon examined in the lower Columbia River reservoirs (Kolok and Rondorf 1987, Muir, 1988 #16100] or Snake River Reservoirs (Curet, 1993). Although observed by the ISG in smolt monitoring stations in the lower Columbia River in 1994 (and noted as common by station workers), they have not been reported in the literature. Based on experiences in the Northwest and worldwide with *Mysis relicta* introductions to lakes and reservoirs (Lasenby et al., 1986, Spencer, 1991 #7793), these predatory invertebrates compete with salmonids for zooplankton food, and can rapidly deplete the zooplankton food supply. When zooplankton is a major substitute for riverine aquatic insects in the food of juvenile salmon (Curet, 1993), competition for it by *Neomysis* could be important for salmonid feeding and growth. Clearly, more study of *Neomysis s* is needed in the Columbia River mainstem.

How *Corophium* and *Neomysis* became established upstream of tidal influence and how they (at least *Corophium*) colonized all the way to Lower Granite Reservoir is not known. Nightengale (personal communication) hypothesizes that the Snake river colonizers were transported upstream in water from below Bonneville Dam by fish transportation barges. *Corophium*, especially *C. salmonis*, requires fine sandy sediments for benthic habitat, a predominant feature of the reservoirs that now occupy the once flowing rapids of the Columbia River basin mainstem. Once inoculated, the populations must have found highly suitable habitat.

e) Nutritional status of juvenile migrants.

There are indications that the nutritional status of outmigrants is now poor. Curet (1993) found that subyearling fall chinook salmon in Lower Granite and Little Goose reservoirs were feeding at only 27 percent of their maximum ration during April-July. This was only 7 percent greater than the estimated maintenance ration that would provide no growth, and it indicated to Curet that there were food limitations in the habitat. The Smolt Monitoring Program observed outmigrant fall chinook salmon in poor physical condition during the recent drought years. This question of nutritional status deserves more research attention than it has been given. Migrants that exist at just above the starvation level can hardly be expected to have good long-term survival.

Whether the newly established *Corophium* is an adequate food substitute for the more normative riverine foods is an important question. Kolok and Rondorf (1987) showed that the consumption of *Corophium* was associated with reduced caloric densities in stomach contents. That is, the amount of usable energy per volume of food material was less than other foods being consumed. (Muir and Emmett, 1988) noted, however, that the low caloric density might be compensated by ease of availability, meaning less energy had to be expended to capture the prey. De La Noue and Choubert (1985) compared the food values of chironomid larvae, daphnia, and a freshwater gammarid amphipod (similar to Corophium) for rainbow trout and found the amphipod to rate poorly. Total and essential amino acids were lowest in the amphipod. Both daphnia and chironomids met the amino acid requirements for salmonids (NRC 1981), but the amphipod was deficient in arginine and lysine. The digestibility was also poorest, with the highest percentage of consumed material being passed as feces. The authors rated the amphipod as "much inferior" to either daphnia or chironomids (which were generally equally good) as an aquaculture food. Thus, the replacement of riverine chironomids by estuarine *Corophium* may well be having a detrimental effect on the nutrition of downstream migrating juvenile salmonids. This inference from published studies needs to be tested by studies of feeding and nutritional status of Columbia River basin fish. Nutritional status can be evaluated by examination of whole body energy content (cal/g). Whole body lipid or fatty acid content are variables that could be very useful, e.g., (Brett, In press #17280].

Comparison of Mid-Columbia and Snake River stocks

A comparison of mid-Columbia and Snake River stocks of salmonids might be fruitful for evaluating the effects of food and feeding on survival. The Hanford Reach has abundant riverine habitat remaining, although flooding has been reduced. The Snake River mainstem is entirely impounded. Food production undoubtedly differs. The mid-Columbia water tends to be clearer with more macrophytes, which may serve as alternative substrates for development of chironomids. *Corophium* may not have colonized the upper mid-Columbia reservoirs, and would, in any case, not proliferate in the flowing Hanford Reach (which may be a barrier to natural upstream colonization). Fish (or other) barge transportation does not occur upstream of Hanford, so colonization by barge bilge water would not occur. These topics deserve attention.

With sketchy information as a basis, a speculative hypothesis for food-chain differences between Mid-Columbia and Snake River fish can be advanced, as follows, based on three main subdivisions of the mainstem (lower reservoirs below the Snake confluence, the Hanford/mid-

Columbia, and the lower Snake River reservoirs) (Figure 5.1). Effects are more acute in warm, low-flow years than when flows are high and water remains cool.

Lower reservoirs: *Corophium* provides an adequate food base for the larger emigrating juvenile salmonids in the lower Columbia River reservoirs in spring and early summer. Though nutritionally deficient, this abundant source adequately feeds both mid-Columbia and Snake River migrants in the lower river (when supplemented with some terrestrial insects and zooplankton), as it normally did in the freshwater estuary below Bonneville Dam. The earlier-migrating Hanford subyearlings are able to make use of this food source. Later migrating Snake River subyearlings arrive in the lower reservoirs after *Corophium* are no longer available in the water column. *Neomysis* competes with late-arriving young salmon for zooplankton, and is not itself eaten. Young salmon in summer are thus poorly fed.

Hanford/mid-Columbia: A typical riverine food chain of nutritious aquatic insects sustains both Hanford stock and upstream migrants through the reach. Reservoir reaches above Priest Rapids Dam and in upper McNary Reservoir upstream of the Snake River confluence have clear water and macrophytes that grow abundant aquatic insects, even where current is slower. Fish enter the lower reservoirs well fed.

Snake River reservoirs: Riverine aquatic insects have disappeared except in the upstream ends of reservoirs. *Corophium*, though abundant, does not enter the water column and thus does not provide alternative food. Warm shoreline water (especially in low-flow years) reduces suitable feeding habitat for underyearling fall chinook in summer, and forces replacement feeding on open-water zooplankton. *Neomysis,* if also in the Snake River reservoirs (not yet reported), competes with salmon for zooplankton. Turbid Snake River water prevents much macrophyte growth and attached aquatic insects. Survival of poorly fed underyearlings is low. Slow growth and low current velocities cause underyearlings to enter the Columbia River late in the migration season when temperatures are high and *Corophium* is not available as an alternative food source for lost riverine aquatic insects. The same factors affect yearlings, but to a lesser degree because they move through the reach earlier and more rapidly.

Overall assessment of mainstem habitat quality for salmonids

This appraisal emphasizes that feeding and growth of juvenile salmonids (and the habitats that promote them) are just as deserving of our attention as factors that affect mortality in the basin (e.g., turbines, predation, gas bubble disease, etc.). There is enough scientific understanding of foods and feeding of juvenile migrants to suggest a major effect of the hydropower system. Because there has been little integrated study of the food chain and fish nutritional status through the mainstem, the scientific base is not yet adequate to ascribe priority of feeding problems relative to other factors that affect juvenile salmonid survival. The best we can do is to advance hypotheses (based on available literature), which should be tested.

Overall Assessment of Tributary Habitat Quality.

The negative influences of logging, grazing, dams, irrigation withdrawals, urbanization, exotic species introductions and other human activities have been documented in all of the Columbia River tributaries. Many, if not all of the larger tributaries are degraded by streamside uses that fail to recognize the importance of riparian vegetation and local upwelling areas (e.g., springbrooks, ponds and wetlands) on flood plains as essential normative features. Some of these habitat problems can be normalized by reregulation of flows as discussed above and detailed in Stanford et al.(1996). In addition, new incentives for streamside stewardship that conserve and enhance connectivity and productivity of floodplain habitats need to be fostered on tributaries as well as mainstem reaches. Special incentives for protection of land-water interface zones are needed in reaches where streamside conditions are normative now as a consequence of a legacy of limited human influences.   Owing to the dramatic escalation of intermountian valley development, in the next decade we could lose remaining productive and connected salmonid habitats (e.g., Stanly Basin on the Salmon River, North and Middle Forks of the Flathead River). For example, cool water refugia exist in the Grand Rhonde (Li et al., 1995) that are critical for salmonids. Such refugia should be accorded special protection before they are purposefully or inadvertently degraded. The Quartz Lake watershed in Glacier National Park is the only example we are aware of in the entire Columbia Basin where an entirely native food web, including the full compliment of native headwater salmonids, remains intact. This and other native fish refuges should be completely protected as native salmonid fishery reserves. Plans for protection of remaining quality habitat and stabilization and normalization of degraded habitats are needed for every tributary in the Columbia Basin. However, it may be prudent to focus actions on those tributaries that have the greatest likelihood of playing a key role in salmonid recovery (e.g., those that are in proximity to currently functional habitats that are producing salmonids such as the Yakama and its potential connectivity to the Hanford Reach of the mainstem Columbia River).

HABITAT CONCLUSIONS (LEVEL OF PROOF)

1. Habitat required for salmonid migration, spawning, incubation and juvenile rearing has been severely degraded in the Columbia Basin by the cumulative effects of flow regulation by dams and diversions, sedimentation from forestry and agricultural activities and massive introduction of non-native biota (fish, invertebrates and riparian plants). (1)
2. Owing to the diverse climates and food web assemblages of the different ecoregions that make up the Columbia River catchment, native salmonids displayed great diversity of life history types (stocks or populations) specifically adapted to the wide array of natural habitats.(1) Diversity has been substantially depleted by habitat loss, fragmentation and degradation. (1)
3. Habitat fragmentation and loss is extensive throughout the Columbia River Basin, except in those few areas where human activities are limited, particularly in roadless and wilderness areas in the upper portions of some sub-basins. (1) Incremental loss of incubation, rearing and spawning sites has reduced or eliminated production of salmonid stocks and disrupted natural metapopulation structure and dynamics. (1)
4. Most alluvial floodplain reaches and associated habitats, historically supporting large, productive spawning populations and providing essential, high-quality rearing habitats for maturing and migrating juveniles, have been destroyed by reservoir inundation, substantially degraded by altered flows associated with hydropower operations or disconnected from the salmon ecosystem by dams that block migratory pathways. (1)
5. Habitat restoration using artificial structures (e.g., weirs, logs cabled into streams, coffer dams, rock gardens) has failed to mitigate the adverse effects of temperature alteration, sedimentation, and simplification of habitat structure and processes caused by upland and riparian land use activities. (2)
6. Presence of non-native fishes is a strong indicator of habitat degradation and is problematic for any restoration effort. (1) Non-native fishes are far less abundant and reproductive in freeflowing segments where native habitats remain in relatively good shape (e.g., Hanford Reach). (2) Native salmonids (and other aquatic vertebrates) remain healthy in less than 5 percent of the headwater streams of the Columbia River tributaries in Idaho, Montana, Oregon and Washington, owing to genetic introgression and displacement by non-native species, which has been mediated by a long history of stocking of cultured brook, rainbow, brown and lake trout in headwater lakes and streams. Adfluvial populations of bull and cutthroat trout have been vastly compromised by food web changes in the big valley bottom lakes (e.g., Pend Oreille, Flathead) as a result of misguided stocking of non-native mysid shrimp and the interactions of these shrimp with non-native fishes. (1)

7. In the Hanford Reach and other alluvial river segments highly productive, flooded riparian zones provided much of the riverine food production (in the form of rapidly colonizing and growing chironomids) for migrants in spring (both underyearlings and yearlings); these critical food web components do not exist in mainstem reservoirs and are substantially reduced or eliminated in riverine segments that are regulated by dams. (1)
8. Typical lake food items (zooplankton) provide an inadequate food source (2) and fish in the Snake River reservoirs are energetically deficient. (2)
9. Food abundance in the mainstem during rearing and migration, which is higher with flooding, may affect salmon survival. (5)
10. Estuarine invertebrates have colonized the lower Columbia River reservoirs and provide a food source that constitutes nearly all in Bonneville Reservoir and about 2 percent in John Day reservoir but are not present in Snake River reservoirs. (2)
11. Estuarine food organisms found in lower Columbia River reservoirs are less nutritional for salmon than riverine food sources but may be adequate if eaten in sufficient numbers. (2)
12. Availability of riverine habitat for producing food and the longitudinal continuity of riverine and estuarine food webs are major differences between successful Hanford stocks (riverine, continuity) and unsuccessful Snake River stocks (reservoirs, discontinuous). (4)
13. Submerged macrophytes in the less turbid Mid-Columbia River without flooding may be a successful alternative substrate for producing riverine, chironomid food for salmon (contributing to success of the Mid-Columbia stocks), whereas submerged macrophytes are less common in the more turbid Snake River. (5)

Uncertainties

1. The exact magnitude and timing of restored flows and temperature regimes need to be empirically determined for specific free-flowing segments and requires a broadly multidisciplinary approach. (However, no uncertainty exists with respect to the need to re-establish flow and temperature seasonality and to stabilize base flow and temperature fluctuations).
2. Although "best management practices" (BMP's) may reduce impacts to habitat compared to unregulated land use, uncertainty about effectiveness of present BMP's must be resolved by scientific evaluation at both site-specific and watershed scales; some results will not be known for decades after implementation. In the face of uncertainty about the sufficiency of current land use practices, designation and protection of a well-distributed network of reserve areas and habitat patches from new land-disturbing activities is necessary to establish experimental natural baselines and to establish a biological hedge against possible failure of BMP's in treated areas.
3. Habitat restoration may be ineffective at restoring native species where introduced non-native species are well-established. Available science suggests that non-natives will be most vulnerable, and many can be effectively suppressed, where habitats are maintained by natural range of flow and temperature variation. However, abrupt changes in reservoir management could temporarily drive existing populations of some non-native fishes into tributary habitats, increasing the risk of their colonization of tributaries. On the other hand, reservoir changes also will likely create new mainstem habitat refugia for native fishes. The risk of dispersal and establishment of non-native fishes will be lowest where tributaries retain relatively natural streamflows, thermal regimes, habitat diversity, and intact native fish assemblages.
4. The mainstem Columbia River may have too many hydropower and irrigation storage reservoirs to ever allow sufficient habitat restoration to allow native salmonid diversity and productivity to substantially recover. However, the surprising resilience and salmon productivity of the Hanford Reach suggests that restoration of critical salmonid habitat is possible without impractical alteration of dam operations.
5. The nutritional state of migrating salmonids requires resolution in relation to stability and productivity of food webs, including importance and effects of colonization of mainstem reservoirs by estuarine species and value of macrophytes for producing food for mid-Columbia salmonids.

Recommendations

1. Free-flowing reaches downstream of hydroelectric dams should be reregulated to re-establish normative flow and temperature regimes and thereby allow the river to naturally restore instream and floodplain habitats and food webs.
2. Restoration of substantial mainstem habitat likely can be accomplished by drawdown of selected reservoirs to expose and restore alluvial reaches (e.g., upper ends of John Day and McNary pools). These options should be quantitatively examined.
3. Habitat restoration should be framed in the context of measured trends in water quality because functional salmonid habitats are characterized by high quality (pure, cool, clear) water and few people will argue with the actions to sustain attributes of high water quality.
4. New timber harvest prescriptions (e.g., selective cutting, attempted fire simulations, salvage logging, road retirement), sustainable agriculture practices, and other land use practices for upland and riparian areas, commonly referred to as best management practices (BMP's), need to be empirically tested and demonstrated as effective in credible short- and long-term studies before they can be considered sufficient for conserving and enhancing water quality and salmonid habitats.
5. If the restoration goal of the FWP and other efforts includes conservation and enhancement of remaining native and naturally reproducing salmonids, all stocking of non-native biota should be stopped in habitats used by or hydrologically connected to habitats required by all life stages of native salmonids (resident and anadromous). Carefully evaluated mechanisms to reduce or eliminate the reproductive capacity or dispersal of non-native species in native salmonid habitats should be implemented if riverine controls (e.g., by restoration of flushing flows) prove ineffective in controlling non-native species.
6. A well-distributed network of reserve watersheds and riverine habitat patches, based on the current distribution of strong subpopulations of native salmonids, should be designated and protected from new land-disturbing activities in order to establish experimental natural baselines for evaluation of effectiveness of management practices and to establish a biological hedge against possible failure of BMP's to conserve and enhance aquatic habitat in treated areas.
7. A study plan should be developed for evaluating the importance of food production to the success of juvenile rearing and outmigration in the Columbia River basin, to include:
    a. Test, through field studies, the nutritional state of migrating Snake River salmonids identified by Curet in relation to that of mid-Columbia stocks, to estimate the importance of food availability to salmon survival;

- b. Estimate, through field studies of insect colonization and growth during flooding and spatial analyses of floodplains, the quantity of salmonid food potentially produced by flooded riparian lands in the lower Columbia-Snake basin and lost by river regulation, and relate quantitatively to the food requirements of migrating juvenile salmon;
- c. Determine, through field studies, the current extent of colonization of reservoirs by estuarine species;
- d. Establish, through laboratory feeding experiments, the suitability of estuarine organisms as food for downstream migrants relative to riverine food organisms;
- e. Estimate, through field studies and laboratory feeding experiments, the importance of longitudinal continuity of food for relative survival of Mid-Columbia (Hanford) and Snake River migrants;
- f. Estimate, through field studies, the value of macrophytes for producing food for Mid-Columbia salmonids; and
- g. Evaluate the nutritional status of juvenile salmonids during transportation from upper river dams to below Bonneville Dam.

8. Provide an integrated assessment of the role of food and feeding on the nutrition of downstream migrants leading to conclusions regarding action options for restoration of riverine food chains (e.g., induced flooding, riparian habitat restoration) and promotion of estuarine food chains (e.g., species stocking).

Analysis Of River Temperature Patterns And Salmon Populations And Habitats

Temperature is a critical habitat variable that is very much influenced by regulation of flow and impoundments. The mainstem reservoirs are relatively shallow and heat up in late summer causing concern for salmon survival. The lower reaches of some key tributaries also are very warm in late summer because they are dewatered by irrigation withdrawals. Due to the extreme importance of temperature regimes to the ecology of salmonids in the basin, temperature information merits special attention as a key habitat descriptor. Therefore, we summarized temperature considerations in the December 1994 Fish and Wildlife Program (FWP or Program) and reviewed our understanding of water temperatures of the Columbia River basin.

Temperature in the Council's Program

Basic assumptions. The Council's Program seems to make the basic assumption that the hydropower system has caused elevated water temperatures, which are detrimental to salmon either directly (introduction to Section 5) or through increased predation (5.7). The Program introduces temperature effects with a figure (Fish and Wildlife Program Figure 1-2) that shows average August-September water temperatures at Bonneville Dam rising since the 1940s. This temperature assumption may not be a valid generalization with respect to maximum temperatures of the main river flows, as indicated in the review summary below. It is a valid concern for a time period of the current peak of adult migration upriver, however.

Maximum temperatures in the mainstem Snake River, where salmon survival is most tenuous, are generally lower in summer than before the series of storage and mainstem reservoirs was installed. This is also true in the mainstem Columbia River. The assumption that temperatures may have increased is correct when applied to temperatures seen in late summer and fall, when the latency of reservoir storage is exhibited. Besides a lowering of maximum summer temperatures, the peak temperatures have been shifted to later in the year. Localized temperature increases have been caused by the hydropower system. In particular, shoreline areas inhabited by underyearling chinook salmon during their summer rearing and outmigration have increased.

The Program also seems to assume that river temperature is linked to volume of flow and water velocity. These are not necessarily linked. Thalweg temperature (the temperature of most of the water volume) and its timing are affected by water storage and release schedules. Localized temperatures and their cumulative effects on thalweg temperatures are affected by reservoir topography more than by river flow rates.

Fall chinook salmon adult migration. During preparation of the 1994 Program, there were recommendations to control (reduce) summer and early fall temperatures to improve survival of adult summer and fall chinook salmon (introduction to Section 5). Temperatures at this time are higher than adults can survive for long periods during late summer and fall migrations. These recommendations are consistent with the seasonal shift in high temperatures caused by increased water storage. A strategy for lowering Snake River temperatures for migrating adults is to retain cold winter water in upstream reservoirs, particularly the Dworshak project (5.1A.2; 6.1D.2; 6.1D.4) and Brownlee Reservoir (5.2A.10; 5.2B.3; 6.1D.4) for release later in the year. Some of this water would be made available through better water management by irrigators (5.2D.2). These actions would be consistent with providing suitably cool temperatures for chinook salmon (see below) , if they are operationally feasible.

Because little of the existing data on temperature requirements of chinook salmon has been obtained for the Snake River stocks, the Program includes studies of baseline temperature effects in its request for baseline life history studies of Snake River fall chinook salmon (7.5B.3). This is a pertinent request, particularly because the Snake river stock that persisted for so long at rather high temperatures may be more thermally tolerant than other strains.

Among localized temperatures, those in fish ladders were of special concern in the Program. The Corps of Engineers is requested to evaluate potential methods for decreasing temperature in mainstem fish ladders and to apply these methods where appropriate (6.1A.1; 6.1B.2). We did not review data on fish ladder temperatures but consider warm water temperatures there in late summer and fall to be consistent with the shift in peak temperatures of mainstem flows to later in the year and withdrawal of fish ladder water from fish exit points near the warm reservoir surface. Use of cooler water from lower strata for fish ladders seems feasible within a mainstem project; control of temperatures of the main river flow is a matter of upstream storage and release timing.

River temperature control. Control of thalweg temperatures in the Columbia River basin requires not only operational actions but the ability to track temperature changes and to predict the effects of possible manipulations. The computer models or river temperature developed by Jaske and Gobel (1967) and Jaske and Synoground (1970) were pioneering efforts in this direction. The Corps of Engineers' COLTEMP model is the version now being used. Several other river temperature models are available in the literature for such use. The Council's Program calls for upgrade of the COLTEMP model based on past temperature control operations and monitoring in the Columbia River basin (6.1D.5). The Program also calls for collection of meteorological, hydrological, and temperature data in the tributaries and mainstem that would affect mainstem temperature (6.1D.6).

Requests for both model improvement and monitoring of data needed as input for the model or its calibration are appropriate. However, the science of thermal modeling is well developed internationally and not a matter of developmental research. Numerous models are available that are adequate to evaluate temperature control options, given sufficient meteorological, hydrological and tributary temperature data for input and sufficient calibration and verification runs of the model.

There are practical limitations to increasing flows in summer and fall to aid adult migrations by lowering temperatures and also doing so in spring to aid smolt outmigration by increasing velocity. Cold "winter water" can be exhausted in upstream reservoirs by spring releases and not be available for late summer and fall cooling (introduction to section 5). Operational constraints raised in the Program are real. The relative benefits of water released in spring and summer/fall have not yet been quantified well in a manner consistent with the best scientific knowledge.

Temperatures in hatcheries. Improved propagation of salmon in hatcheries includes provision of suitable temperatures (7.2D). Although there are no specific measures directed toward temperatures in hatcheries, the specific measures on prevention of diseases, improvement in breeding and husbandry practices, and so forth can logically include the abundant data on temperature effects.

Temperatures in tributaries. The Program recommends that habitat restoration efforts in tributaries maintain temperatures in historically useable spawning and rearing habitat at less than 60F, not to exceed 68F (7.6D). It also directs the Forest Service to monitor temperatures as streams leave federal lands and to strive for the 60F recommendation at these points (7.8A.6). This temperature recommendation is consistent with current knowledge. The Program also calls for investigations of methods for controlling temperatures of releases of dams (Detroit, Cougar, Blue river) in the Willamette River basin, to restore temperatures to near pre-project levels (7.9A). Investigation of temperature effects is also called for in the Grande Ronde River basin (7.9C). These requests seem reasonable, although there are temperature problems in many other locations in the Columbia River basin that were not called out (lower Yakima River, Okanagan River, upper John Day River, lower Grande Ronde and Imnaha rivers, and others).

Temperatures during juvenile outmigration. Little was said in the Program specifically about temperatures during juvenile outmigration. However, it is clear from sections on flow and velocity that the Council believes increased flow will also lower river temperatures. As noted above, these factors are not necessarily linked. The Program called for temperature monitoring during the drawdown of John Day reservoir (5.4C.4).

Current State of Science

Water temperatures. Water temperatures in the Columbia River basin have been altered by development and are, at times, suboptimal or clearly detrimental for salmonids. High temperatures alone can be directly lethal to both juvenile and adult salmonids in the Snake River in summer under recent conditions, based on generally accepted thermal criteria (National Academy of Sciences/National Academy of Engineering 1973) and measured temperatures (Karr, 1992).

Temperatures are generally lowest in January and February and highest in August and September (Ebel et al., 1989). Thermal regimes in tributaries throughout the basin differ widely with location, elevation, and input from rainfall, snowmelt, glaciers and aquifers. In general, cold runoff from mountainous tributaries gradually warms as the water progresses downstream. The principal flow of mainstem rivers is warmest near the Columbia River outlet, where temperatures peak near 21°C (70° F). Clearly, there are exceptions in dry , low flow years. Development of tributaries such as the Yakima, Okanagan, and Umatilla rivers for agriculture and urbanization has resulted in their outlets to the mainstem reaching summer temperatures about 4°C above levels expected otherwise. Historically, average temperatures at the mouth of the Snake River during August and September have always been a few degrees higher than those in the mainstem Columbia (Roebeck et al. 1954; Jaske and Synoground 1970).

Effects of dams have been investigated at several scales. Studies in the 1960s (Jaske and Goebel, 1967) showed that the construction of river-run reservoirs on the mainstem of the Columbia River caused no significant changes in the average annual water temperature. However, storage and release of water from Lake Roosevelt had delayed the timing of peak summer temperatures below Grand Coulee Dam since 1941. This delay was about 30 days at Rock Island Dam and was reflected as far downstream as Bonneville Dam near the river's outlet. Temperature extremes in the mainstem were moderated by the reservoir complex so that river below Grand Coulee is now somewhat cooler in summer and warmer in winter. This trend is particularly evident in tailwaters of major storage reservoirs such as Brownlee, Hells Canyon, and Dworshak where high storage to flow ratios hold cold bottom water in the reservoir for release through deep outlets until well into summer. Mainstem reservoirs in the Snake and Columbia rivers have created shallow, slowly-moving reaches of shorelines where solar heating has raised temperatures of salmon rearing habitat (especially for underyearling fall chinook) above tolerable levels, negating this as usable habitat for much of the summer) (Curet, 1993; Key et al., 1995).

Water temperatures in lower tributaries were generally low enough prior to European settlement to allow summer outmigrations of subyearling smolts. This life history strategy is essentially gone today when we have intolerably high late spring and summer temperatures. Watson (1992) describes characteristics of the lower Yakima River that coincided with a subyearling smolt life history. Much of the lower mainstem Yakima River consisted of intricately braided channels flowing through dense riparian forests. The shading, combined with lack of warm irrigation water now prevalent probably resulted in water temperatures considerably lower than today. Haggett (1928) in (Watson et al., 1992) reported that heavy outmigrations of underyearling smolts began in June, peaked in mid-July, and continued through September. Similar timing is still found in the Rogue River (Schluchter and Lichatowich, 1977). Today, any smolt leaving the Yakima must do so nearly two months earlier (although some forays toward the lower river in summer still occur, perhaps as a way of testing the system for migration opportunities; Lichatowich, personal communication). The original braiding and complex of side channels probably retained cooler water from springtime flows in river gravels so that overall lower river temperature was cooled.

A similar problem occurs in the lower reaches of other tributaries. Largely because of water withdrawals for irrigation and removal of riparian vegetation, water temperatures in summer are higher than those known to be lethal or debilitating to salmonids. Streams known to be so affected include the Umatilla, Grande Ronde, and Okanagan. These high temperatures have prevented juvenile fish from migrating or redistributing downstream or to tributary branches. Adult fish have been prevented from ascending to suitable spawning areas. Unsuitable temperatures have served to fragment the habitat of tributary basins (see metapopulation discussion in Chapter 4).

<u>Salmon temperature requirements</u>. Temperature effects on salmonids have been studied extensively, both in general and in the Columbia River basin. There is a firm scientific basis for temperature requirements and the measures that could be taken in the Fish and Wildlife Program (FWP). It remains unclear whether the specific temperature management measures in the FWP make best use of this information, however.

Tolerance levels of salmonids for elevated temperatures at all life stages are well understood. An Interagency Columbia River Thermal Effects Study in the late 1960s focused on temperature effects on Columbia River basin salmonids (Rulifson 1971). As part of that interagency study, much thermal effects research was conducted in the Hanford Reach (Tempelton and Coutant 1970). There has been considerable literature developed since that time, especially in other basins where chinook salmon have been threatened. Several relevant reviews of the literature have been written recently (Brown, 1976; Groot and Margolis, 1991).

Knowledge about overall habitat requirements and migration mechanisms of salmonids and the relationships to temperatures of these habitats have not, however, been adequately accommodated in management decisions.

Responses to temperature are expected to be somewhat variable within the species (see Beacham and Murray 1990). Chinook salmon occur from Alaska to the Central Valley of California. Stocks have evolved or been selected through both natural selection and hatchery practice to tolerate quite divergent environmental conditions and habitats. The degree to which the data summarized here (largely for hatchery stocks) is representative of the migratory wild populations generally and of the Columbia River basin particularly is undetermined.

Temperature requirements differs by life stage. Most literature reviews categorize thermal requirements by life stage in the following sequence: (1) adult migration, (2) spawning, (3) egg and embryo incubation, (4) juvenile rearing. Types of thermal effects information are grouped within these categories. The summarized information usually consists of the type of observation (e.g., peak spawning temperature), the temperature at which the observation is reported to occur, and the literature reference in which it is reported. Anecdotal evidence is often included as well as rigorous testing.

The ISG concludes from available information that the thermal requirements for chinook salmon are approximately as follows. Optimum generally covers several degrees above and below the stated value; stressful is performance markedly below optimum; lethal is for standard 1-week exposures (higher temperatures may be tolerated for short-duration exposures). Other salmon species are not markedly different.

> *adult migration and spawning:* optimum 50°F (10°C), with a range of about 46.4-55.4°F (8-13°C); stressful >60°F (15.6°C); lethal >70°F (21°C)
>
> *incubation:* optimum <50°F (<10°C), with a range of about 46.4-53.6°F (8-12°C); stressful >56°F (13.3°C); lethal >60°F (15.6°C)
>
> *juvenile rearing:* optimum 59°F (15°C) with a range of about 53.6-62.6°F (12-17°C); stressful >65°F (18.3°C); lethal 77°F (25°C)

Documentation of the past temperature control work called for in the present program has been largely in ad hoc reports of limited distribution, e.g., (Karr, 1992), which has restricted productive review of their scientific basis by the ISG. In general, the studies have shown that the cooling effect of planned releases at tributary dams is noticeable in the Snake River but diminishes with distance downstream. The temperature control projects seem nearly devoid of the underlying biological basis for such actions, especially any emphasis on temperatures in the actual habitats used by salmon. A more thorough review of the actions and their basis is needed before it is possible to say whether the management approaches are sound.

TEMPERATURE CONCLUSIONS (And Levels of Proof):

1. The FWP assumes that the hydropower system has generally raised water temperatures and that mainstem river temperature is linked to flow and water velocity. These are oversimplifications based on current knowledge, and inadequate for effective remedial measures.
2. Storage impoundments in the Columbia River basin have shifted annual peak temperatures of the mainstem thalweg (all the way to the ocean) to later in the season, when late summer and fall migrating salmonids encounter them. This has occurred even though annual average temperatures have not changed. Tailwaters of storage reservoirs are colder than normal in summer and warmer in fall and winter, but selective withdrawal systems are being installed to provide more natural thermal regimes. (1)
3. Nearshore reservoir waters of the mainstems used by underyearlings are warmed to levels rarely seen in the unimpounded rivers. (1)
4. There is abundant information in the scientific literature on the thermal requirements of the major salmonid species, based on research in the Columbia River basin and elsewhere, which can be used to evaluate and manage thermal effects on fishes. This information indicates that temperatures can exceed lethal levels and often exceed temperatures suitable for successful growth and development. (1)
5. Temperature models and monitoring have been used to track and manage river temperatures for benefit of fish, but documentation of these efforts is inadequate for peer review. (2)
6. Temperature has been identified as a problem in more circumstances than are addressed in the FWP. (1)

Temperature Global Conclusion:
High temperatures in the late summer and fall are detrimental to both juvenile and adult salmon in the mainstem and tributaries, but recent efforts to model and monitor temperatures and manage temperatures for salmonids are too poorly documented to allow independent peer review.

Critical Uncertainties:
For adequate independent peer review, the major critical uncertainty is the status of documentation of temperature monitoring, modeling, and management programs in the basin.

Recommendations:

1. Develop better documentation of temperature programs for peer review.
2. Consider annual temperature cycling as part of the normative river and continue efforts to provide storage reservoirs with selective withdrawal systems to move toward the normative condition.
3. Consider temperature in tributaries as part of the environmental change that has fragmented salmonid habitat, and develop programs to move temperatures there to a more normative condition.

Table 5.1 Discharge statistics and basin areas of the Columbia River and its major tributaries.

River Station Name and Location	Average Discharge (cfs)	Discharge Extremes (cfs) Maximum	Discharge Extremes (cfs) Minimum	Drainage Area above Station (sq. mi.)	Average Discharge per Sq. Mi. above Station (cfs)	Period of Record
Columbia:	71,300	377,000	8,940	34,000	2.10	1913-1970
Columbia at Birchbank, Br. Col.						
Columbia at The Dalles, Ore.	194,000	1,240,000	12,100 (dam closure)	237,000	0.82	1878-1970
Kootenai:						
Kootenay at Newgate, Br. Col.	10,490	98,200	994	7,660	1.37	1930-1970
Kootenai at Porthill, Idaho	16,030	125,000	1,380	13,700	1.17	1904-1927 1928-1970
Pend Oreille-Clark Fork:						
Clark Fork above Missoula, Mt.	2,930	31,700	340	5,999	0.49	1929-1970
Pend Oreille below Box Canyon, near Ione, Wash.	28,220	125,700	125	24,900	1.13	1952-1970
Snake:						
Snake near Heise, Idaho	6,806	60,000	460	5,752	1.18	1910-1970

Snake below Ice Harbor Dam, Wa.	1966-1970 range:	298,000	0 (dam-testing)	108,500	0.36-0.53	1907-1917 1962-1970
Willamette-Middle Fork of Willamette:						
Middle Fork of Willamette near Oakridge, Ore.	765	39,800	209	258	2.96	1958-1970
Willamette at Wilsonville, Ore.	28,350	339,000	3,600	8,400	3.38	1948-1970

Source: Date from the U.S. Geological Survey, 1972-1976 (Patrick, 1995)

Table 5.2. Year in operation, length of reservoir, year in service of juvenile salmon collection facilities, location of PIT tag detectors and deflectors, and year in service and capacities for barges and trucks for hydroelectric dams of the Columbia Basin.

DAM	YEAR OF INITIAL SERVICE	LENGTH OF RESERVOIR
Columbia River		(miles)
Rock Island (RM 453.4)	1933	21
Bonneville (RM 145.5)	1938	46
Grand Coulee (RM 596.6)	1941	151
McNary (RM 292)	1953	61
Collection Facilities	*1979*	
Chief Joseph (RM 545.1)	1955	52
The Dalles (RM 191.5)	1957	24
Priest Rapids (RM 397.1)	1959	18
Rocky Reach (RM 473.7)	1961	42
Wanapum (RM 415.8)	1963	38
Wells (RM 515.1)	1967	29
John Day (215.6)	1968	76
Snake River		
Brownlee (SRM 285)	1958	57
Oxbow (SRM 273)	1961	12
Ice Harbor (SRM 9.7)	1961	32
Hells Canyon (SRM 247)	1967	22
Lower Monumental (SRM 41.6)	1969	29
Collection Facilities	*1992*	
Little Goose (SRM 70.3)	1970	37
Collection Facilities	*1975*	
Lower Granite (SRM 107.5)	1975	39
Collection Facilities	*1976*	

* Barge and Truck Transportation-1976, truck transport began; 1977, barge (2) use began; 1981, barges (3) and trucks (5) expanded; 1982, barges (4) expanded, trucks (5); 1990, new barges (2) added; now at full capacity: 6 barges (296,000 pounds of fish), 5 trucks, 3 mini-tankers.

* Juvenile PIT tag detection system-currently installed at Lower Granite, Little Goose, Lower Monumental, McNary, John Day, and Bonneville Dams. Source: Corps of Engineers (1984), Athearn (1994)

Table 5.3. Fishes of the Columbia River basin.

Common Name	Scientific Name	Anadromous Marine Freshwater	Locality	Native Introduced
Pacific lamprey	*Entosphenus tridentatus* (Gairdner) (or *Lampetra tridentata*?)	A	Widespread in basin	N
River lamprey	*Lampetra ayresi* (Gunther)	A	Widespread in basin. WA, OR, ID	N
Western brook lamprey	*Lampetra richardsoni* (Vladykov and Follett)	F	Coastal, mouth of Columbia	N
Green sturgeon	*Acipenser medirostris* (Ayres)	MF	Lower Columbia and marine	N
White sturgeon	*Acipenser transmontanus* (Richardson)	A	Widespread in basin. WA, OR, ID	N
Arctic grayling	*Thymallus arcticus*		Introduced	
Golden trout	*Salmo aguabonita*		Introduced	
American shad	*Alosa sapidissima* (Wilson)	A	Abundant and increasing	I
Yellowstone cutthroat	*Oncorhynchus bouveri*		Native in Snake Plateau	
Lake whitefish	*Corregonus clupeaformis* (Mitchill)	F	Banks Lake, WA. Occurs ID	I
Chum salmon	*Oncorhynchus keta* (Walbaum)	A	Lower river	N
Coho salmon	*Oncorhynchus kisutch* (Walbaum)	A	Lower river. Upriver runs extirpated.	N
Sockeye salmon (kokanee)	*Oncorhynchus nerka* (Walbaum)	A	Two lakes in WA. One ID. Extirpated 24 others. Introduced various inland waters.	N
Chinook salmon	*Oncorhynchus tshawytscha* (Walbaum)	A	Widespread. Some stocks low.	N
Mountain whitefish	*Prosopium williamsoni* (Girard)	F	Widespread	N
Pygmy whitefish	*Prosopium clarkii*			N
Cutthroat trout	*Oncorhynchus clarki*	F (A)	Widespread. Common in smaller tributaries	N

Rainbow trout (steelhead)	*Oncorhynchus mykiss*	AF	Widespread. Abundant in tributaries	N
Atlantic salmon	*Salmo salar* (Linnaeus)	AF	Rare in Columbia River. Escapees from aquaculture.	?
Brown trout	*Salmo trutta* (Linnaeus)	F	Locally in WA, ID and OR	I
Brook charr	*Salvelinus fontinalis* (Mitchill)	F	Scattered streams and lakes	I
Bull charr	*Salvelinus confluentus*	F	Widely distributed. Abundance varies	N
Lake charr	*Salvelinus namaycush* (Walbaum)	F	Scattered lakes	I
Interior redband	*Oncorhynchus gibbsi*			N
Surf smelt	*Hypomesus pretiosus* (Girard)	M (F)	Mostly marine. Occasionally freshwater. WA, OR	N
Eulachon	*Thaleichthys pacificus* (Richardson)	A	Abundant seasonally in lower river	N
Westslope cutthroat	*Oncorhynchus lewisi*			N
Grass pickerel	*Esox americanus vermiculatus* (LeSueur)	F	Two lakes in eastern basin. WA	I
Northern pike	*Esox lucius* (Linnaeus)	F	Pend Oreille Lake. Coeur d'Alene River. ID	I
Chiselmouth	*Acrocheilus aleutaceus* (Agassiz and Pickering)	F	Widespread and abundant in WA, ID, and OR	N
Goldfish	*Carassius auratus* (Linnaeus)	F	Uncommon in Col. R. Abundant in scattered lakes. WA, OR, ID	I
Lake chub	*Couesius plumbeus* (Agassiz)	F	Restricted. Upper Columbia, WA, ID	N
Carp	*Cyprinus carpio (*Linnaeus)	F	Widespread. Abundant, WA, OR, ID, MT	I
Tui chub	*Gil bicolor* (Girard)	F	Abundant eastern Col. basin, WA, OR, ID	N
Utah chub	*Gila atraria* (Girard)	F	Snake River drainage. ID	I
Leatherside chub	*Gila copei* (Jordan and Gilbert)	F	Snake River drainage. ID	I
Oregon chub	*Hybopsis crameri* (Snyder)	F	Willamette River. OR	N

Fathead minnow	*Pimephales promelas* (Rafinesque)	F	Snake River drainage. ID	I
Peamouth	*Mylocheilus caurinus* (Richardson)	F	Abundant Columbia River, WA, OR, ID	N
Northern squawfish	*Ptychocheilus oregonensis*	F	Widespread and abundant. WA, OR, ID, MT	N
Longnose dace	*Rhinichthys cataractae* (Valenciennes)	F	Widespread. WA, OR, ID	N
Leopard dace	*Rhinichthys falcatus* (Eigenmann and Eigenmann)	F	Common in upper Columbia. WA, OR, ID	N
Speckled dace	*Rhinichthys osculus* (Girard)	F	Widespread and abundant. WA, OR, ID	N
Redside shiner	*Richardsonius balteatus* (Richardson)	F	Widespread. Abundant. WA, OR, ID	N
Tench	*Tinca tinca* (Linnaeus)	F	Rare. Columbia River. Spokane River. WA, OR, ID	I
Utah sucker	*Catostomus ardens* (Jordan and Gilbert)	F	Snake River drainage, ID	N
Longnose sucker	*Catostomus catostomus* (Forster)	F	Widespread. Abundant. WA, ID	N
Bridgelip sucker	*Catostomus columbianus* (Eigenmann)	F	Locally abundant in upper Columbia drainages. WA, OR, ID	N
Bluehead sucker	*Catostomus discobolus* (Cope)	F	Snake River drainage. ID	N
Largescale sucker	*Catostomus machrocheilus* (Girard)	F	Widespread. Abundant. WA, OR, ID, MT	N
Mountain sucker	*Catostomus platyrhinchus* (Cope)	F	Restricted. Upper Columbia drainages. WA, OR, ID	N
Black bullhead	*Ictalurus melas* (Rafinesque)	F	Rare. WA, OR, ID	I
Channel catfish	*Ictalurus punctatus* (Rafinesque)	F	Abundant. Middle reaches. WA, OR, ID	I
Tadpole madtom	*Notorus gyrinus* (Mitchill)	F	Rare. WA, OR, ID	I
Flathead catfish	*Pylodictus oliveris* (Rafinesque)	F	Snake River drainage. ID. Possibly OR	I
Sandroller	*Percopsis transmontanus* (Eigenmann and Eigenmann)	F	Widespread. Common tributaries. WA, OR, ID, MT	N
Burbot	*Lota lota* (Linnaeus)	F	Common in deep lakes. WA, OR, ID, MT	N

Three spine stickleback	*Gasterosteus aculeatus* (Linnaeus)	MF	Widespread and abundant. WA, OR, ID, MT	N
Striped bass	*Morone saxatilis* (Walbaum)	A	Rare at mouth of Columbia. WA, OR	I
Green sunfish	*Lepomis cyanellus* (Rafinesque)	F	Klamath River, OR	I
Pumpkinseed	*Lepomis gibbosus* (Linnaeus)	F	Locally abundant. WA, OR	I
Smallmouth bass	*Micropterus dolomieui* (Lacepede)	F	Common in middle reaches. WA, OR, ID	I
Largemouth bass	*Micropterus salmoides* (Lacepded)	F	Abundant. WA, OR, ID	I
White crappie	*Pomoxis annularis* (Rafinesque)	F	Abundant lower reaches, esp. McNary pool. WA, OR, ID	I
Black crappie	*Pomoxis nigromaculatus* (Lesueur)	F	Potholes. WA	I
Yellow perch	*Perca flavescens* (Mitchill)	F	Abundant in some lakes. Rare in tributaries. WA, OR, ID, MT	I
Walleye	*Stizostedion bitreum* (Mitchill)	F	Common and abundant in river. WA, OR, ID	I
Shiner perch	*Cymatogaster aggregata* (Gibbons)	M	Tidewater. Abundant. WA, OR	N
Starry flounder	*Platichthys stellatus* (Pallas)	M	Occasionally in freshwater. WA, OR	N
Coastrange sculpin	*Cottus aleuticus* (Gilbert)	F	Lower river to Bonneville Dam. WA, OR	N
Shorthead sculpin	*Cottus confusus* (Bailey and Bond)	F	Bonneville Dam. Usually higher altitude tributaries. WA, OR	N
Mottled sculpin	*Cottus bairdi* (Girard)	F	Common. Upper Columbia drainages. WA, OR, ID, MT	N
Piute sculpin	*Cottus beldingi* (Eigenmann and Eigenmann)	F	Common. Upper Columbia drainages. WA, OR, ID	N
Slimy sculpin	*Cottus cognatus* (Richardson)	F	Rare. Tributaries to Lake Chelan. WA	N
Shoshone sculpin	*Cottus greenei* (Gilbert and Culver)	F	Snake River drainage. ID	N
Torrent sculpin	*Cottus rhotheus* (Smith)	F	Common. Widespread. WA, OR, ID	N

Prickly sculpin	*Cottus asper* (Richardson)	FE	Common. Estuary and lower river to Hanford reach. WA, OR	N
Margined sculpin	*Cottus marginatu*s (Bean)	F	Restricted. Umatilla River to Walla Walla River. WA, OR	N
Riffle sculpin	*Cottus gulosus* (Girard)	F	Lower Columbia to Cowlitz and Lewis Rivers. WA, OR	N
Reticulate sculpin	*Cottus perplexus* (Gilbert and Evermann)	F	Overlaps with C. gulosus and may hybridize	N
Pacific staghorn sculpin	*Leptocottus armatus* (Girard)	M(F)	Primarily marine. Occasionally freshwater. WA, OR	N
Spoonhead sculpin	*Cottus ricei*			

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