NOAA Technical Memorandum NMFS-NWFSC-69

Role of the Estuary in the Recovery of Columbia River Basin Salmon and Steelhead:

An Evaluation of the Effects of Selected Factors on Salmonid Population Viability

September 2005

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

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This document should be cited as follows:
Fresh, K.L., E. Casillas, L.L. Johnson, and D.L. Bottom. 2005. Role of the estuary in the recovery of Columbia River basin salmon and steelhead: an evaluation of the effects of selected factors on salmonid population viability. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-69, 105 p.

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An Evaluation of the Effects of Selected Factors on Salmonid Population Viability

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September 2005

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Executive Summary

The primary purpose of this technical memorandum is to evaluate the potential of selected factors associated with the Columbia River estuary to improve viability of listed anadromous salmonids in the Columbia River basin. We examine how the estuary supports viability of anadromous salmonid populations, review what is known about juvenile salmon in the Columbia River estuary, examine how changes in selected factors associated with the estuary have potentially affected salmon, and describe an approach to value the contribution to salmon population viability derived from potentially reducing a factor's impact. This evaluation was conducted in support of efforts by NOAA Fisheries Service to revise deficiencies identified by Judge J. A. Redden in the 2000 Biological Opinion on the effects of the federal Columbia River Power System (FCRPS) on listed anadromous populations in the basin.

For this review, we defined the Columbia River estuary broadly to encompass the entire continuum where tidal forces and river flows interact. The upstream extent of the estuary is Bonneville Dam and the downstream extent includes the plume. Geomorphic features, ecological functions, and physical characteristics vary broadly within this area and give rise to a mix of habitats that juvenile salmon can potentially occupy. The importance or function of any unit of estuarine habitat depends on site specific or patch scale attributes such as vegetation type, substrate type, and salinity regime. In addition, habitat functions depend on the landscape context of that habitat, such as its size, shape, location in the estuary, the composition of surrounding habitat, and connectivity with other habitats. Throughout the entire estuary, the distribution and quality of habitats has been affected (and continues to be affected) by a variety of anthropogenic (e.g., urbanization) and natural (e.g., climate) factors.

Our understanding of the role of the estuary in the life history and ecology of salmonid populations has changed considerably over the past century. Initial perspectives about the estuary were that it was unimportant or irrelevant because the estuary (and ocean) was considered to be limitless in its ability to support salmon. Thus the major factors affecting salmon were considered to be density-dependent factors occurring in freshwater. Eventually, scientists became aware that nonfreshwater factors had an important influence on numbers of returning adult salmon and began to consider the role that the estuary and ocean played in salmon population fluctuations. The estuary was viewed as a bottleneck or limiting factor to the numbers of adults that could be produced. Attempts to remove or bypass the bottleneck (e.g., by releasing juveniles from hatcheries or transporting fish rapidly through the estuary) proved unsatisfying at increasing abundance of adults. In more recent years, the estuary has come to be regarded as part of the continuum of ecosystems that salmon need to utilize in order to complete their life cycle, rather than a place that salmon need to avoid.

Fundamental to the view that estuaries are an important part of the life history of salmon is the concept that anadromous salmonids are comprised of populations, or discrete breeding units, that vary with respect to their spatial and temporal use of habitats. Variability in climate,

instream flow conditions, harvest practices, hatchery operations, and accessibility of habitats by adults and juveniles help define how populations use estuarine habitats, including arrival timing in the estuary, duration of estuarine residence, and fish size at the time of estuarine entry.

NOAA Fisheries Service defines the status of anadromous salmonids based on the viability of populations or groups of populations (evolutionarily significant units or ESUs) over long time-frames. For populations and ESUs to recover, the risk that they will go extinct needs to decline. Four viable salmonid population (VSP) performance criteria are used to define viability: abundance, productivity, spatial structure, and diversity. Levels of these attributes in aggregate define extinction risk or persistence of the population; all four VSP criteria are critical to recovery and are interrelated. This approach to evaluating population status differs from traditional salmon management, which assessed the status of anadromous salmonids from a production perspective using primarily numbers of harvested fish, numbers of reproducing adults, or survival. Estuarine habitats clearly contribute to the viability and persistence of salmon populations in a number of ways. The amount of estuarine habitat that is accessible affects the abundance and productivity of a population. The distribution, connectivity, number, sizes, and shapes of estuarine habitats affect both the life history diversity and the spatial structure of a population. Attributes of estuarine habitats (e.g., temperature and salinity regimes, food web relationships) affect diversity and productivity of populations as life-stage specific survivals vary with habitat characteristics.

Ideally, we would like to be able to link factors in the estuary to their potential to affect the viability of each listed population or ESU. However, because we do not have specific, empirical information describing estuarine habitat use at the population level, we used an alternate approach. We evaluated effects of candidate factors on the main life history type expressed by an ESU and the range of life history strategies utilized by each ESU. As each ESU is comprised of a number of populations, we then inferred responses of the populations based on what we predict will occur for the ESU.

Each listed ESU in the Columbia River basin—the lower Columbia River coho salmon (*Oncorhynchus kisutch*) ESU was also included—was classified as expressing either a stream-type or ocean-type behavior based on when juveniles arrive in the estuary and their size at arrival. When viewed over long time-scales, most members of ocean-type populations migrate to sea early in their first year of life after spending only a short period (or no time) rearing in freshwater. Most members of stream-type fish migrate to sea after rearing for more extended periods in freshwater, usually at least a year. Thus ocean-type fish tend to spend longer periods in ocean habitats compared to stream-type populations.

Individual members within each population employ a variety of alternative life history strategies or approaches to using available habitat. A life history strategy describes if, how, when, and for how long individual salmon use various habitats throughout the freshwater, estuarine, and ocean landscape. We used two attributes associated with use of estuarine habitats—size of fish at estuarine entry and time of estuarine entry—to define six general life history strategies that can potentially be expressed by all anadromous populations: 1) early fry, 2) late fry, 3) early fingerling, 4) late fingerling, 5) subyearling, and 6) yearling. Although each life history type can produce members that use each strategy, the relative proportion of members associated with each strategy varies by life history type. Ocean-type populations are dominated

by the fry and fingerling strategies while stream-type populations are dominated by the yearling strategy.

Of the possible estuarine factors that could potentially affect viability, we considered the effects of four on salmon in the Columbia River estuary: flow, predation, habitat, and contaminants/toxics. These four were selected from a larger list of factors affecting salmon in the estuary based on whether: 1) a significant change in the factor from historical conditions was evident, 2) the factor could potentially affect population viability, 3) there was quantitative data available that could be used to analyze effects of the factor, and 4) the factor could be linked to hydropower operations in the Columbia River basin. The selection of factors relied primarily on the first three criteria. We did not use the fourth criteria to exclude evaluation of any factor.

A brief evaluation of changes in each factor and how the factor could affect population viability was conducted based on existing data and analyses. We only considered impacts on juvenile life stages and did not include potential impacts on adults during their return migration. From these overviews, we developed a series of hypotheses or assumptions about each factor that helped guide how we rated their relative importance for each ESU.

It is important to note that our analyses were not inclusive of all factors that may have a significant affect on salmon population viability. For example, we expect that water temperatures have warmed from historical levels, which could exclude some habitats from use by juveniles during part of the year and affect metabolic processes of both salmon and their predators. These changes in water temperature could alter mortality rates. The intent of our evaluation was to lay out a framework for future consideration of other factors that may affect juvenile salmon use and benefits from estuarine habitat as more comprehensive information becomes available.

River flow is a fundamental factor affecting characteristics of juvenile salmon and their habitat in the estuary and plume. The interaction of flow and tides with the land creates and maintains estuarine habitat. Large-scale changes in flow occur as a result of spatially explicit interactions of short- and long-term climate cycles—El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), respectively—with the watershed. Operations of the Federal Hydropower system (e.g., generation of electricity, flood control, and irrigation) have had significant affects on attributes of flow, including reducing the mean annual flow, reducing the size of spring freshets, almost completely eliminating overbank flows, and changing the timing of ecologically important flow events. The hydrological changes, along with floodplain diking, represent a fundamental shift in the physical state of the Columbia River estuarine ecosystem.

Major changes in the estuary resulting from flow alterations that are especially relevant to salmon include a loss of vegetated, shallow water habitats and changes in the size, seasonality, and behavior of the plume. Such changes potentially have significant consequences for both expression of salmonid diversity and productivity. In particular, because the changes in habitat are most pronounced in shallow water areas, we predict that effects on the ESUs and life history strategies (the fry and fingerling strategies) that make the most extensive use of these shallow water areas will be especially significant. Further, we predict that altering and reducing plume size, shape, and intensity will also affect ESUs expressing the yearling life history strategy.

The location and types of habitats present in the Columbia River estuary have been substantially altered from historical conditions. Although the entire estuary has not yet been surveyed, the main changes that have been identified to date have been a major loss of emergent marsh, tidal swamp, and forested wetlands; shifts in organic matter important to estuarine food webs; and changes in features of the plume. Shallow water-dependent life history strategies (fry and fingerlings) have been most affected by the loss of shallow water-vegetated habitat types in the estuary, while larger life history strategies have been most affected by changes in the plume. Alterations in attributes of flow and the construction of dikes and levees have caused these changes. Diking is an especially significant change because it severs the connection of the habitat with the river, eliminating any direct (use) or indirect (export of organic matter for food webs) benefit to the fish.

Exposure to waterborne and sediment-associated chemical contaminants has the potential to affect survival and productivity of both ocean- and stream-type stocks in the estuary. Stream-type ESUs are likely to be most affected by short-term exposure to waterborne contaminants such as current use pesticides and dissolved metals. These chemicals can disrupt olfactory function and interfere with such behaviors as capturing prey, avoiding predators, imprinting, and homing. Ocean-type ESUs may also be exposed to these types of contaminants, but will also be affected by persistent, bioaccumulative toxicants such as poly chlorinated biphenyls (PCBs) and DDTs, which they may absorb during their more extended estuarine residence. Consequently, we expect that the impact of contaminants on ESUs exhibiting the ocean life history type will be more significant.

Predation is a major source of mortality of all salmonid populations. Although many predator-prey interactions in the Columbia River estuary appear to have changed from historical conditions, we have little quantitative data on most predators. One exception is Caspian tern (*Sterna caspia*) predation, which has significantly increased recently due to a change in nesting habits of the birds in the Columbia River estuary. The main impact of tern predation is on ESUs with stream-type life history types, especially steelhead (*Oncorhynchus mykiss*). This is primarily because the dominant migratory periods employed by salmonids with a stream-type life history most overlap with the nesting period of the terns. Improvements to productivity of populations by managing terns would be expected to especially benefit stream-type ESUs, although lesser benefits to other salmonid ESUs in the basin should also occur.

To evaluate effects of factors on population viability, we developed a rating system that ranked each factor as having a high, medium, or low ability to improve the status of anadromous salmon populations if the impact of the factor was substantially reduced. We drew inferences about how a factor affects an ESU based on the life history type of the ESU and how the factor would affect the different life history strategies that characterized that life history type. Because the currently available information regarding use of the estuary does not allow resolution at the level of a population, limiting factors for all stream-type ESUs were ranked similarly while those for ocean-type ESUs were ranked similarly. Ratings were developed by considering each factor relative to other estuarine factors within an ESU; we did not consider the effect of factors relative to other nonestuary factors.

The rating system used to evaluate effects of factors on population viability consisted of two screening levels; each level addressed two major issues. The level 1 screen evaluated

whether the factor was likely of concern to an ESU based on its affects on VSP and change in the factor relative to historical conditions. The level 2 screens asked how the factor affected an ESU based on where the affects occurred. Each question was evaluated for each factor for each ESU based on whether the ESU was ocean-type or stream-types. Scoring was done using guidance from the principles/hypotheses developed in the analyses of the limiting factors. Because of limitations in our knowledge base, we aggregated the estuary into two zones—river mouth to Bonneville Dam and the plume. From the river mouth to Bonneville Dam, we only differentiated two habitat types—shallow and deep.

For ocean-type ESUs, for example, Columbia River chum salmon (*Oncorhynchus keta*) and Snake River fall Chinook salmon (*O. tshawytscha*), flow and habitat were rated as having a high ability to affect population viability. As noted above, flow changes in the basin are primarily a result of dam operations, whereas habitat changes are a function of both hydropower operations and other, nonhydro issues, notably the construction of dikes and levees in the estuary. The combined affect of flow and habitat changes on estuarine habitat has been to reduce the amount of shallow water habitat (especially vegetated habitat such as swamps and marshes) and disrupt organic matter inputs from these vegetated habitats. The dominant life history strategies of ocean-type Chinook salmon extensively use shallow water habitat, which is where the main flow and habitat changes have occurred. Moreover, the beneficial use of shallow water habitat by each ESU is likely a function of location in the estuary. Whereas all estuarine-dependent life history strategies expressed by each ESU will use the lower portion of the estuary (mouth of the Columbia River to RM 40), upriver ESUs (e.g. Snake River fall Chinook salmon) will be more dependent on tidally influenced shallow freshwater habitats between Bonneville Dam (their point of entry to the Columbia River estuarine system) and approximately RM 40. Tern predation was considered to have a low affect on the ocean life history type because terns do not prey significantly on fry and fingerling-sized fish (the dominant ones associated with this life history type). Contaminants received a medium score. Both waterborne and sediment contaminants can affect fry and fingerling life history strategies in shallow water areas.

For stream type ESUs (e.g., Snake River spring/summer Chinook salmon and mid-Columbia River steelhead), the primary estuarine factors affecting population viability were tern predation and flow; both of these factors were ranked as medium. Tern predation was ranked in the medium category because it is primarily directed at subyearling and yearling size fish, which are the dominant strategies in stream-type ESUs. In addition, these larger fish occur in deeper water channel habitats where they are most vulnerable to the terns and migrate at a time when they are most susceptible to tern predation. Flow changes were ranked medium for stream-type ESUs because both abundance and productivity were affected by changes in plume habitat. In addition, the main life history strategies for these ESUs are most abundant in plume habitats where they would be expected to be most vulnerable to flow-related changes in plume habitat.

From the perspective of the estuary, we conclude that population viability of stream-type ESUs is most affected by tern predation and flow, while flow and habitat most affect ocean-type ESUs. At this time, we do not know how much of a change in each factor is required to affect improvements in population responses of relevant ESUs. Based on available information, we hypothesize that the greatest opportunity to affect ESUs in the Columbia River basin by the manipulation of estuarine factors is with restoration of shallow water habitat. These actions will primarily affect ocean-type ESUs and the shallow water-dependent strategies of stream-type

ESUs. This is because there is a strong linkage between the fry and fingerling life history strategies, which dominate ocean-type ESUs, and shallow water habitat. Thus the main affect on ocean-type ESUs of making changes in habitat and flow will be realized as gains in abundance and productivity. The main affect on stream-type ESUs of reducing tern predation and altering flow will also be realized as gains in abundance and productivity.

There is a large amount of vegetated shallow water habitat that has been lost due to the combined effects of flow changes and diking. These two factors must be considered in concert in considering restoration approaches because of the strong effects of flow on functions of shallow water habitat. Restoration of shallow water habitat can be done without changing hydropower operations (which can have other, unintended consequences, such as an increase in gas bubble disease). However, we expect that studies now underway will provide greater insight into how much change and where such change in shallow water is both possible and needed to affect population viability.

Acknowledgments

We thank Jennifer Burke for her insights and discussions on many aspects of salmon use of the Columbia River estuary. Critical reviews of this document were provided by Jennifer Burke, Si Simenstad, Joyce Howard, Mary Ruckelshaus, Tim Beechie, Lynne Krasnow, John Ferguson, and Cathy Tortorici. We thank Casey Rice, Eric Beamer, Curtis Roegner, A. D. Robertis, and Paul Moran for sharing unpublished data sets. Our thanks to Dave Ward for helping with the subsection on northern pikeminnow predation.

Introduction

Since 1991, 12 different groupings or evolutionarily significant units (ESUs) of anadromous salmonids that reproduce in the Columbia River basin have been listed as threatened or endangered under the Endangered Species Act (ESA) of the United States. These include steelhead (*Oncorhynchus mykiss*), chum salmon (*O. keta*), Chinook salmon (*O. tshawytscha*), and sockeye salmon (*O. nerka*) populations that spawn from the upper Snake River basin to tributaries of the lower river below Bonneville Dam. Every subbasin of the Columbia that is currently accessible to anadromous salmonids contains at least one threatened or endangered population. The Federal Columbia River Power System (FCRPS) has had a variety of well documented impacts on anadromous salmonids in the basin, including the loss and degradation of spawning and rearing habitat and increased mortality of upstream and downstream migrating fish during passage at hydroelectric facilities (ISG 2000, Williams et al. 2005). As a result, efforts to recover these populations at risk have focused almost exclusively on identifying and modifying risk factors directly associated with the large hydroelectric dams constructed throughout the basin.

In recent years, increasing attention has been directed at the role of other hydropower related issues and nonhydropower-related issues in the decline and recovery of salmonids in the basin. One such issue is changes in the condition and availability of habitats in the estuary. The growing recognition that the estuary has a role in the recovery of Columbia Basin salmonids represents a significant departure from previous management efforts in the system. Several developments appear to be responsible for this change. First, legislation Congress passed in 1996 amended the Power Act and required the Northwest Power Planning Council (NWPPC) to consider the effect of ocean conditions on fish and wildlife populations when recommending hydropower mitigation projects for the Columbia River basin. This legislation focused new attention on the estuary, plume, and coastal ocean habitats.

Second, life stage risk and sensitivity modeling analyses of Columbia River salmon populations by Kareiva et al. (2000) and McClure et al. (2003) suggested that additional actions beyond passage improvements were needed to recover salmonid populations. Two life stages identified as sensitive to perturbations included the first years spent rearing in the river, estuary, and ocean. Kareiva et al. (2000) used a matrix population model to conclude that the maximum potential to contribute to anadromous salmonid recovery was associated with these life stages. However, they could not discriminate between these life stages nor could they determine how much of a change in survival was possible.

Third, scientific perspectives of the life history and ecology of anadromous salmonids have shifted in recent years (Bottom et al. 2005). Previously, habitats and life stages important to salmon were considered in isolation with the goal of identifying single limiting factors restricting salmon production. We now recognize that marine, estuarine, and riverine environments are each components of an extended salmon ecosystem that cannot be treated independently (NRC 1996, Bisbal and McConnaha 1998, ISG 2000). Thus the estuary, which includes the plume, is part of the continuum of landscapes all juvenile and adult anadromous

salmonids use that originate from the Columbia River basin. They connect freshwater and marine habitats and are used by all life stages to some degree for feeding, refugia from predators, and physiological transition (McCabe et al. 1983, 1986, Bottom and Jones 1990).

Finally, our understanding of the relationships between habitats and the persistence of salmon populations has evolved in recent years. It is clear that habitats cannot be valued simply on the basis of their role in producing fish biomass or numbers (Bottom 1997). Instead, diverse habitats and the expression of life history strategies based on use of these habitats are directly linked to salmon population viability (i.e., persistence) over long time scales (McElhany et al. 2000). These linkages were explicitly recognized by the Independent Scientific Group (ISG) for the NWPPC, which concluded that estuary and ocean dynamics help to control salmon productivity (Beamish and Bouillon 1993, Beamish et al. 1999) and that salmon biodiversity (including the diversity of estuarine life histories) helps to reduce the effects of fluctuations in ocean, and presumably freshwater, conditions (ISG 2000). Alterations and loss of estuarine habitats thus has direct implications for salmonid population viability.

The challenges of identifying, designing, implementing, and evaluating recovery actions in the estuary are significant, in part because we know little about the estuary and the salmon that use the estuary. While ongoing research efforts will significantly upgrade our knowledge base in upcoming years, much of what we now know is conceptual or based on research from other areas, such as Puget Sound. Estuary restoration at any scale is a challenge and in the Columbia River estuary it is an especially daunting challenge because of the massive size of this system. Further, the estuary is among the most heavily modified portions of the basin (Thomas 1983) due to the long history of coastal development and the cumulative effects of flow regulation, habitat modification in the estuary, and other changes upriver which have altered sediment transport and salinity regimes in the system (Simenstad et al. 1992, Weitkamp 1994). In the last 100 years, these and other changes have decreased the amount of some types of wetland habitats in this region by as much as 70% from historical levels (LCREP 1999).

The primary purpose of this technical memorandum is to evaluate the potential of selected factors associated with the estuary to improve viability of listed anadromous salmonids in the Columbia River basin. Accordingly, we:

1) examine how the estuary supports viability of anadromous salmonid populations,
2) review what is known about juvenile salmon in the Columbia River estuary (which includes the plume),
3) examine how changes in selected factors associated with the estuary have potentially affected salmon populations, and
4) describe an approach to value the contribution to salmon population viability resulting from reducing the impact of a factor.

These analyses were conducted in support of efforts by NOAA Fisheries Service to address deficiencies identified by Judge J. A. Redden in the 2000 Biological Opinion on the effects of the Federal Columbia River Power System (FCRPS) on listed anadromous populations in the basin.

Columbia River Estuary

An estuary is generally defined as a semienclosed coastal body of water with a free connection to the open ocean in which salt water is diluted with runoff from the land (Pritchard 1967). For this review, however, we define the Columbia River estuary more broadly to encompass the entire continuum where tidal forces and river flows interact, regardless of the extent of saltwater intrusion. Thus the upstream boundary of the estuary is Bonneville Dam, which is the extent of tidal influence, while the downstream boundary includes the plume (Figure 1).

The estuary can be divided into different zones based on a variety of attributes, such as geomorphic features, ecological functions, tidal conditions, salinity regimes, and physical characteristics. A number of approaches have been employed to describe and classify the different zones of the estuary (e.g., Johnson et al. 2003). In this report, we consider only two zones of the estuary, primarily because our information on use of the estuary by juvenile salmon does not yet allow us to discriminate use at a finer scale. The first zone extends from the mouth upstream to Bonneville Dam and includes conditions ranging from the tidally influenced freshwater in the upper estuary to higher salinities and higher wave energies near the river's mouth. The second zone is the river plume, which is generally defined by a reduced-salinity contour near the ocean surface of 31 parts per thousand. During high flows, the plume front is readily visible as a sharp interface between sediment-laden river water and the clear ocean. Its geographic position varies greatly with seasonal changes in river discharge, prevailing nearshore winds, and ocean currents. During summer months, the plume extends far to the south and offshore along the Oregon coast; during the winter it shifts northward and inshore along the Washington coast. Strong density gradients between ocean and plume waters create relatively stable habitat features where organic matter and organisms can be concentrated.

Throughout the estuary is a mix of habitats that the juvenile salmon can occupy. Habitat is the physical, biological, and chemical characteristics of a specific unit of the environment occupied by a specific plant or animal. Thus habitat is unique to specific organisms and encompasses all the physiochemical and biological requirements of that organism within a spatial unit. The function of any estuarine habitat for juvenile salmon depends on site specific or patch scale attributes such as vegetation type, substrate type, and salinity regime (Simenstad and Cordell 2000). In addition, habitat functions depend on the landscape context of that habitat (Simenstad 2000). Landscape context refers to the spatial arrangement of habitat, including its size and shape; location of the habitat within the estuary; the composition of surrounding habitat; and connectivity with other habitats (Turner 1989). A variety of systems have been employed (and others continue to be developed) to classify and describe the diverse array of habitats present in the estuary that vary in their basic philosophical approaches, information that is used, scope, complexity, and application. Table 1 presents a general classification of major habitat types within the estuary below RM 46, after Thomas (1983) and Johnson et al. (2003); habitat classification systems have not yet been developed for other parts of the estuary.

Figure 1. The Columbia River estuary extends from the upper extent of tidal influence at Bonneville Dam (RKm 235), through the oligohaline zone of the river mouth, into the coastal zone including the plume in the Pacific Ocean. (Reprinted from Bottom et al. 2005.)

Table 1. Major types of estuarine habitats and some of their important attributes in the Columbia River below RM 46. (Adapted from Thomas 1983 and Johnson et al. 2003.)

Major habitat types	**Important attributes**
Tidal swamps	Vegetation is mostly shrub and woody species. Higher elevations. Low water velocities.
Tidal marshes	Dominant vegetation varies. Includes emergent marshes. Tidal channels often present. Depths generally range from mean lower low water (MLLW) to above mean higher high water (MHHW). Low water velocities.
Tidal flats	Depths range between MLLW and 6 ft below MLLW. Usually not vegetated.
Medium deep	Depths range from 3–18 ft below MLLW. Mostly associated with medium sized and larger channels. Higher water velocities.
Deep	Depths >18 ft. Mostly associated with the main channel. Higher water velocities.

Use of Estuarine Habitats by Columbia River Salmonids

There have been few studies of habitat use of the Columbia River estuary by wild juvenile salmon and steelhead, and most of this work has been conducted downstream of Puget Island. Research recently initiated by NOAA Fisheries Service in the middle and lower estuary and plume will significantly upgrade our knowledge about how juvenile salmon, specific populations, and ESUs use the estuary. Most of our knowledge about how juvenile salmon use estuaries has come relatively recently from studies in Puget Sound, British Columbia, and Alaska (e.g., Parker 1971, Stober and Salo 1973, Kaczynski et al. 1973, Reimers 1973, Mason 1974, Bailey et al. 1975, Fresh et al. 1979, Salo et al. 1980, Healey 1979, 1980, 1982, Simenstad et al. 1982). It is remarkable that given the overall importance of Columbia River for salmon in the Pacific Northwest and the large size and diversity of this estuarine system, empirical knowledge about how salmon use this estuary is distinctly lacking compared to other estuarine systems in the Pacific Northwest.

An important factor that needs to be considered in any analysis of estuarine habitat use by wild salmon and steelhead is the occurrence of hatchery fish. Because our ability to separate wild and hatchery fish captured in the estuary has been limited and remains so even at present, many of the spatial and temporal patterns observed in previous data sets may apply to hatchery fish rather than wild fish (e.g., Dawley et al. 1985, 1986).

River Mouth to Bonneville Dam

In the portion of the estuary between Bonneville Dam and the river's mouth, one study that provided enough information to distinguish use of different estuarine habitats by juvenile salmonids was by Columbia River Estuary Data Development Program (CREDDP); however, sampling in this program was limited to the lower estuary (to the upstream end of Puget Island). In general, McCabe et al. (1986) found that subyearling Chinook in shallow intertidal habitats of the Columbia River were smaller than subyearlings captured in deeper pelagic areas. Larger yearling migrants spent little time in shallow estuarine habitats and more time in deeper channel areas (Bottom et al. 1984, McCabe et al. 1986).

Most of what is known about juvenile salmon use of the estuary concerns timing of fish passage through the estuary and was derived from seining studies conducted to recapture coded wire tagged (CWT) fish below Bonneville Dam. In the late 1970s and early 1980s, subyearling Chinook salmon (these are all nonyearling fish combined) were present year round in the estuary (Bottom et al. 1984, Dawley et al. 1986, McCabe et al. 1986). While in many of the years studied overall peak abundance occurred from May to September, there were years when a bimodal distribution was observed (Dawley et al. 1985, 1986). There was also evidence of specific patterns in seasonal timing that particular populations exhibited (e.g., Lewis River) that

were different than the patterns for all populations considered in aggregate (Dawley et al. 1985). Peak catches at Jones Beach, where much of the estuary timing work has been conducted, often were highly correlated with the timing of hatchery releases.

Since 2001 NOAA Fisheries Service has investigated habitat relationships of juvenile salmon in the area upstream of the river mouth. Similar to the work by Dawley et al. (1985), juvenile salmon were present in the estuary year round. However, the number of size classes of juvenile salmon passing through the estuary is considerably reduced from historical levels (Figure 2).

Although knowledge of habitat use in the Columbia River estuary is limited, the information that does exist, in combination with studies in other estuaries of the Pacific Northwest, provides insight into how juvenile salmonids use habitats in this large estuary. Estuarine research has demonstrated that juvenile salmon are generally distributed based on water depth (e.g., Healey 1980, Levy and Northcote 1982, Simenstad et al. 1982, Bottom et al. 1984, Levings et al. 1986, McCabe et al. 1986, Miller and Sadro 2003). The smallest size classes tend to be the most closely associated with shallow water. As fish size increases, fish use a broader array of depths; fish size can change as a result of growth that occurs in the estuary, growth in freshwater, or some combination of rearing in the two environments. Habitat shifts by the juvenile salmon do not necessarily occur continuously as fish size increases, but may occur at specific size thresholds. For example, Simenstad et al. (1980) suggested that juvenile chum salmon shifted from use of littoral to offshore habitats at a size threshold of about 50 mm. Based on this size based model, the smallest juvenile salmon in the Columbia River estuary (fry and fingerlings) will be primarily associated with the shallowest, most peripheral, wetland type of habitat, while the larger subyearlings and yearlings will be found in deeper pelagic areas. Coincident with the fish size/depth relationship, smaller salmon tend to spend longer in the estuary and larger yearling migrants spend less time.

Columbia River Plume

Studies of use of the Columbia River plume were initiated in 1998 by NOAA Fisheries Service. In general, the plume is primarily used by yearlings and less so by subyearlings which appear to stay closer to shore (Emmett et al. 2004). Thus far, because sampling has been conducted in late spring and early summer, the distribution of fish in summer is unknown. Although they were not specifically studying use of the plume, Fisher and Pearcy (1995) found relatively few yearlings near the mouth of the Columbia River in summer. The evidence obtained to date suggests the plume serves juvenile salmon in multiple ways. Pearcy (1992) hypothesized that one function of the plume was to distribute juvenile salmon offshore, away from predation pressure closer to the shore. Findings by NOAA Fisheries Service are consistent with the hypothesis proposed by Pearcy (1992). In May and June when flows are higher, juveniles are found further offshore, in the low saline waters, than when flows are lower (Figure 3). During years when river flow out of the Columbia River during the freshet period is reduced, salmon are more localized around the mouth of the Columbia River.

In addition, the plume appears to provide a place for juvenile salmon to feed and grow (Schabetsberger et al. 2003). It may support juvenile salmon foraging by facilitating primary production during the spring freshet period. During low-flow years, such as observed in 2001,

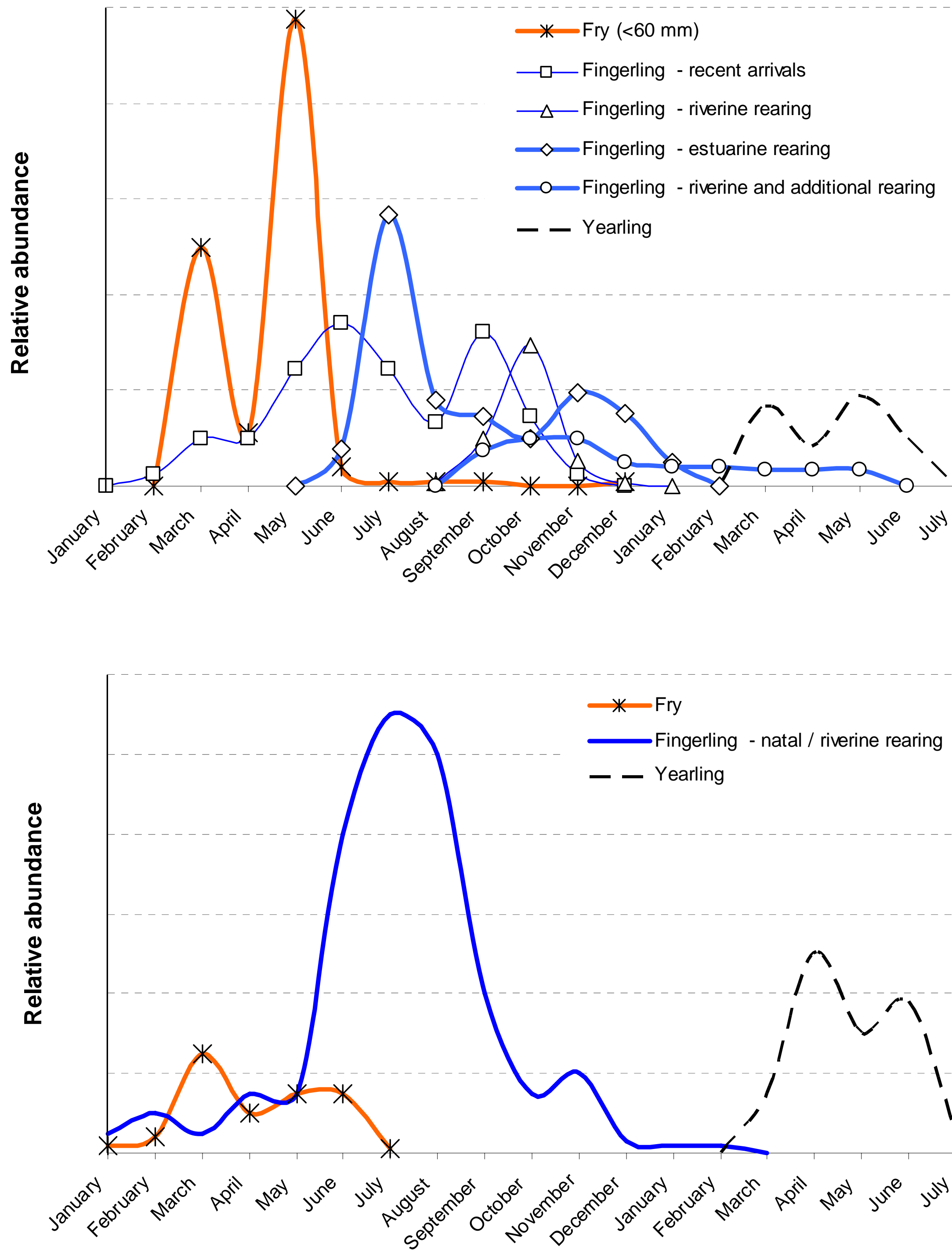

Figure 2. Historical and contemporary early life history types for one broodyear of Chinook salmon in the Columbia River estuary. Historical timing and relative abundance (top) inferred from historical sampling throughout the lower estuary (Rich 1920). Contemporary timing and relative abundance (bottom) derived from Dawley et al. (1985) sampling at Jones Beach. (Adapted from Burke 2005.)

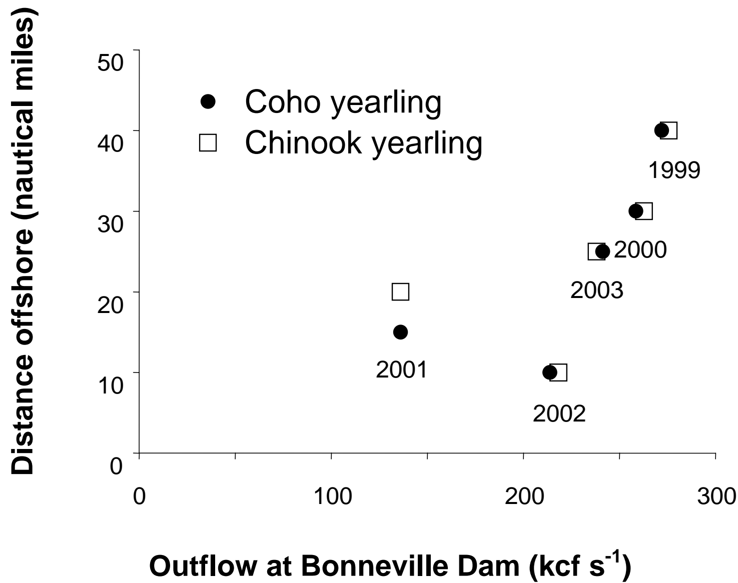

Figure 3. Relationship between average river flow (thousand cubic feet per second) registered at Bonneville Dam for 10 days prior to sampling in the Columbia River plume in May, and the maximum distance offshore juvenile Chinook and coho salmon were captured in surface trawls along a transect extending east along latitude 46.15, just south of the mouth of the Columbia River. (From B. Peterson, NWFSC.)

the amount of chlorophyll evident off of the Oregon and Washington coast affiliated with the plume, as characterized with satellite observations by SeaWifs, was much lower than that observed when more normal flows occurred, such as observed in 1999 (Thomas et al. 2003). Zooplankton biomass is also highly associated with frontal features at the plume margins (Figure 4) and less so either within the plume or oceanic zones.

Some of the ongoing plume research being conducted by NOAA Fisheries Service has focused on identifying attributes of the plume that can be used to define habitat important to juvenile salmon. Features such as the surface area of the plume, the volume of the plume waters, the extent and intensity of frontal features, and the extent and distance offshore of plume waters are considered physical attributes defining habitat important to salmon. One hypothesis that has been studied is that juvenile salmon would preferentially utilize frontal features; this, however, has not been validated. Juvenile salmon abundance was not higher exclusively around frontal features. Studies did suggest that smaller juvenile salmon showed a significant preference for the plume and front habitats as compared to the more marine, oceanic habitats (Figure 5). NOAA Fisheries Service has also found that salmon continue their preference for the low saline environment of the plume as they retain their orientation to the surface region (Emmett et al. in press). The higher turbidity associated with the low salinity plume waters may provide a refuge from predators.

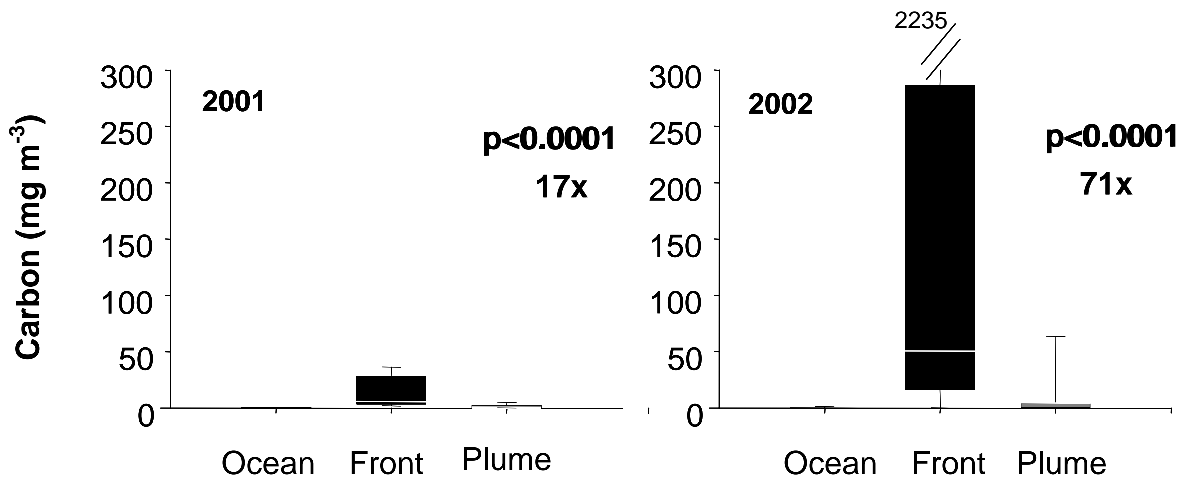

Figure 4. Biomass (milligrams carbon per cubic meter) of megalopae (*Cancer magister*) captured in May 2001 and 2002 in the ocean, front, and plume habitats using a neuston net. Box plots demarcate the 10th, 25th, 50th, 75th, and 90th percentiles. An analysis of variance (ANOVA) (blocked) was used to identify significant differences. Biomass of this species was 17 and 71 times higher in the front habitat compared to the average of the ocean and plume habitats (Morgan et al. in press).

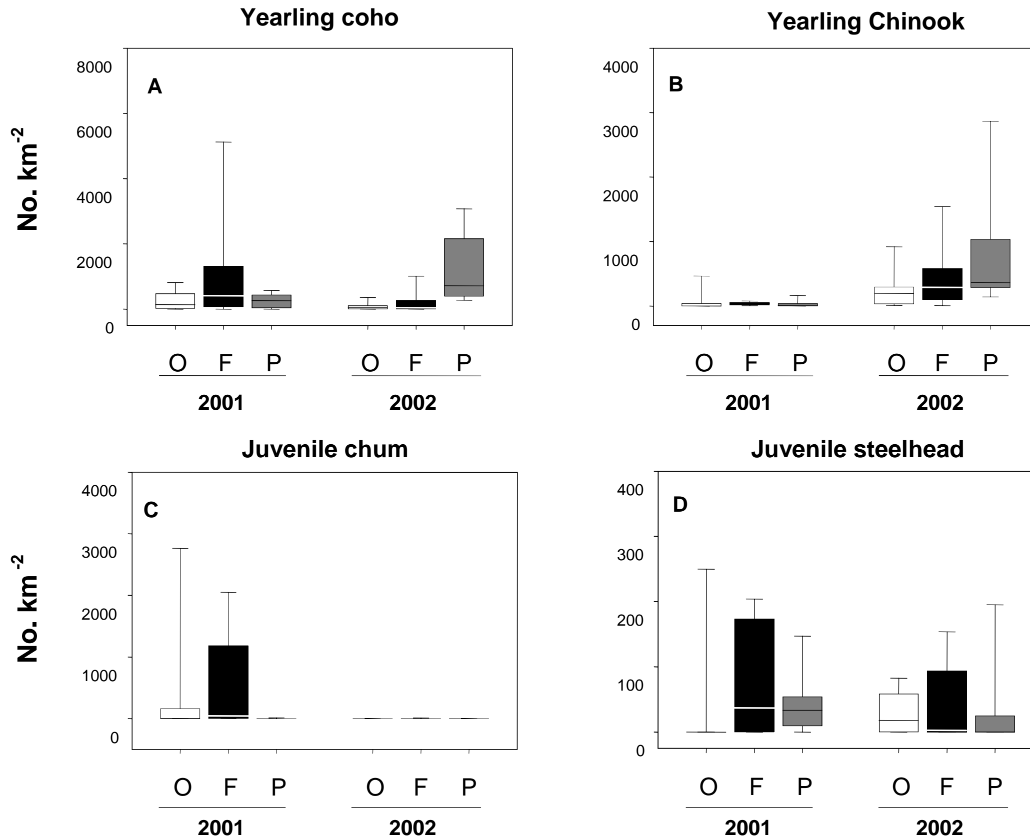

Figure 5. Abundance of A) yearling coho salmon, B) yearling Chinook, C) juvenile chum salmon, and D) juvenile steelhead captured in ocean (O), front (F), and plume (P) habitats using a Nordic rope trawl. Box plots demarcate the 10th, 25th, 50th, 75th, and 90th percentiles of densities. (From A. D. Robertis, NWFSC.)

Role of the Estuary in the Recovery and Management of Salmon Populations

The following section describes our conceptual framework of the role of the estuary in the life history of anadromous salmonids and how this perspective has evolved. It is intended to help structure our evaluation of the potential of selected factors to affect salmonids in the Columbia River basin and to help facilitate recovery and management of anadromous salmonids. The framework describes and organizes our current understanding of how the estuary supports anadromous salmonid species and integrates information on the life history and ecology of salmon, conservation biology, and how estuarine ecosystems function. We incorporated elements of the model that Bottom et al. (2005) developed to guide research on juvenile salmonids in the Columbia River estuary. Because of the lack of knowledge specifically about juvenile salmon in the Columbia River estuary, we used relevant information from throughout the Pacific Northwest to help develop the framework. We recognize that the estuary is much larger than most systems on the Pacific coast where juvenile salmon use of estuaries has been studied, so information from other systems needs to be applied carefully. But, because the salmon are using the estuary for the same fundamental purposes and estuaries have many of the same attributes regardless of size, we believe that principles of estuarine use can be developed from these other systems and applied in the Columbia River estuary.

Historical Views of the Role of the Estuary

Our understanding of the role of the estuary in the life history and ecology of salmon has evolved as we have learned more about how juvenile salmon use estuarine habitats. Initially, the estuarine and ocean environments were considered limitless in their ability to support salmon and so were believed to be unimportant or irrelevant. At this time, freshwater, density dependent factors were assumed to regulate salmon species (Bottom 1997, Bottom et al. 2005), with more adults expected simply as a result of an increase in the number of eggs and fry. A major goal of early salmon research and management was to understand freshwater sources of mortality so that they could be more easily manipulated and more adults could be produced (Bottom 1997). Salmon were viewed primarily from a production perspective as simply another agricultural product or crop to be managed for the benefit of people (Bottom 1997). The output of this crop was defined as short term changes in the numbers of harvestable or reproducing adults.

One outgrowth of the production approach to salmon management has been the use of hatchery fish throughout the Pacific Northwest. Because of habitat destruction and alteration, the high demand for salmon, overharvest, and the expanding human population, there has never been enough harvestable salmon to go around (Lichatowitch and McIntyre 1987). Hatcheries evolved as a way to increase salmon abundance and were based on the freshwater-centric, density-dependent philosophy that more adults would result in direct proportion to the additional number of eggs that survived (Lichatowitch 1999). Hatcheries focused on bypassing as much of

the freshwater life of salmon as possible, where the most significant sources of mortality were believed to occur.

The continued failure of hatchery production to increase or even maintain salmon numbers raised new questions about whether passage through estuaries and the ocean might be critical to determining numbers of returning adults. Salmon researchers in the 1950s and 1960s began to recognize that nonfreshwater factors had a role in determining numbers of returning adults (e.g., Manzer and Shepard 1962, Gilhousen 1962). The development and analysis of long-term data sets on salmon production suggested freshwater conditions could not by themselves adequately explain variability in numbers of returning adults (e.g., Salo and Bayliff 1958, Hunter 1959, Gilhousen 1962, Parker 1968, Peterman 1978). Beginning in the late 1960s, research on the estuarine and early marine life of juvenile salmon rapidly expanded throughout the Pacific Northwest.

Initially, scientists adopted the production-oriented view that estuaries were a bottleneck to salmon production. This bottleneck concept was based on research suggesting that juvenile salmon mortality during this period could be especially high (e.g., Parker 1968, Bax 1983). The estuarine and early marine period came to be regarded by many researchers as the critical period of salmon life that significantly affected overall survival rates and adult returns (Kaczynski et al. 1973, Peterman 1978, Healey 1980, Nickelson 1986, Pearcy 1992).

In the 1970s, proposed expansions in hatchery production generated concerns that there could be a limit or carrying capacity to estuarine and coastal environments. Simenstad et al. (1980) expressed concern that the carrying capacity of the Hood Canal, Washington estuarine environment for pink salmon (*O. gorbuscha*) and chum salmon would be exceeded if enough hatchery fish were released. Bailey et al. (1975) suggested that releases of hatchery pink and chum salmon in Alaska coastal areas could exceed carrying capacities of estuaries for hatchery fish and result in fewer than expected adult returns. Studies were initiated to estimate the quantities or carrying capacity of hatchery fish that could be supported by estuaries (e.g., Reimers et al. 1979) and to find the optimum conditions in the estuary that would maximize production. Because some managers questioned whether salmon were really estuarine dependent, further studies were conducted to ascertain whether the estuary could be bypassed altogether and so render moot the issue of carrying capacity in this environment (MacDonald et al. 1988, Solazzi et al. 1991).

Current Views of the Role of the Estuary: Population Perspective

In more recent years, we have shifted from the more production-oriented views of the estuary to the developing perspective that the estuary is part of the continuum of ecosystems that salmon utilize to complete their life cycle, rather than a place that should be avoided. Estuaries, as well as other places used by salmon throughout their lives, are therefore necessary and important parts of the salmon life cycle. Fundamental to this view of estuaries is the concept that salmon species are comprised of populations. Populations are geographically discrete, self perpetuating, and semiisolated (in terms of genetic exchange) groups of reproducing salmon. They are the unit that much of modern research and management of salmon is organized around. The population perspective of salmon is in part an outgrowth of studies by Willis Rich on Columbia River salmon (e.g., Rich 1920, 1939). Rich evaluated scale patterns of juveniles

passing through the Columbia River estuary and found a variety of patterns of estuarine use. Fish exhibited a wide diversity in the time at which they arrived in the estuary, the amount of time they were spending there, and the size at which they arrived (Rich 1920, 1939); some salmon were present nearly year round in the estuary.

To explain these observations, Rich (1939) suggested that the Columbia River estuary was a mixing ground of fish from many different sources or populations, each of which exhibited a range of behaviors that were defined by the particular set of conditions found in the full range of spawning and nursery areas available to the population. He concluded that there was not a unique or singular way for a salmon species or population to use the estuary or any other habitat. Instead populations employed a diversity of approaches that were determined by variability in climate, instream flow conditions, origin of the fish, harvest practices, hatchery operations, and accessibility of habitats by adults and juveniles. Groups of salmon became locally adapted to the conditions they experienced.

The concept that habitat use by salmon can depend on the population of origin is supported by a wide body of literature (e.g., Wilmot and Burger 1985, Burger et al. 1985, Beachum and Murray 1987, Burgner 1991, Healey 1991, Wood 1995, Woody et al. 2000, Hodgson and Quinn 2002, Miller and Sadro 2003, Ramstad et al. 2003). Our understanding of the specifics concerning between- and within-population variability in estuarine habitat use is still increasing. However, what we know is consistent with the population perspective of habitat use. For example, Beamer[1] has found that early migrating Chinook salmon fry in the Skagit River, Washington, use a different suite of Puget Sound habitats than later migrating fish. Reimers (1973) was able to define different patterns of estuarine habitat use and seaward movement in Chinook salmon in the Sixes River, Oregon, and link those to their ultimate success (i.e., survival). Carl and Healey (1984) concluded that variations in migration behavior and estuarine use within the Nanaimo River, British Columbia basin were linked to different subpopulations associated with geographically distinct spawning areas.

The Estuary and Viability of Anadromous Salmonid Populations and ESUs

NOAA Fisheries Service's Northwest Fisheries Science Center (NWFSC) developed a conceptual approach to evaluating the status of anadromous populations and ESUs that defines status based on a population's viability over long time scales (McElhany et al. 2000). The authors defined a viable population or ESU as one that has a negligible risk of extinction over a 100-year time period. For populations or ESUs to recover, the ability of a population or ESU to persist must increase over time, or conversely, the risk that they will go extinct needs to decline (McElhany et al. 2000). Four viable salmonid population (VSP) performance criteria are used to define viability (McElhany et al. 2000): abundance, productivity, spatial structure, and diversity. All four VSP criteria are critical to the viability of salmon populations, all are interrelated, and levels of all four attributes in aggregate define extinction risk or the likely persistence of the population or ESU. This approach to evaluating population status differs from traditional salmon management, which typically assessed the status of anadromous salmonids from a production

[1] E. Beamer, Skagit River System Cooperative, La Connor, WA. Pers. commun., February 2004.

perspective using numbers of harvested fish or reproducing adults. Using the NOAA Fisheries Service VSP criteria incorporates a much broader view of how to define population status. This perspective recognizes that factors affecting salmon populations vary widely, so using a variety of metrics can provide insight into what types of actions are needed to help populations and ESUs recover.

Abundance is a measure of the number of members in the population (e.g., numbers of spawners or returning adults), while productivity is the rate of growth of the population over a given time interval. Productivity can also be expressed as life-stage specific survivals, since the cumulative effects of those survivals results in a population's growth rate over time. Populations that have a lot of members and a positive population growth rate are more likely to persist than populations that do not have these characteristics. Changes in abundance and productivity of a population can be measured over multiple time scales. Evidence clearly suggests that estuarine habitats contribute to the abundance and productivity of salmon populations (e.g., MacDonald et al. 1988). For example, Reimers (1973) demonstrated that for the one broodyear of Chinook salmon that he studied in the Sixes River, Oregon, most adult returns originated from fish that made extensive use of the estuary. Magnusson and Hilborn (2003) similarly concluded that survival to adult return of hatchery Chinook salmon populations in coastal environments was directly and positively correlated with the condition of the estuary. The Kareiva et al. (2001) matrix population model suggested that improving survival during the estuarine and early ocean stages could significantly increase salmon population growth rates. Changes in conditions in the nearshore zone of Puget Sound, which serves as an extension of the estuary, account for significant variability in adult returns of Skagit Bay Chinook salmon.[2]

Although conservation of diversity and spatial structure are emerging paradigms in recovery and management of Pacific Salmon (e.g., McElhany et al. 2000, Waples et al. 2001, Hilborn et al. 2003, Issak et al. 2003) and other fish species (e.g., Gresswell et al. 1994), their application to salmon recovery remains a considerable challenge. For example, within Puget Sound, quantitative abundance and productivity goals have been developed for many threatened Chinook salmon populations, but population specific goals for spatial structure and diversity do not yet exist. Moreover, guidance on improving spatial structure and diversity in salmon recovery has thus far focused primarily on the effects of spawning characteristics (i.e., amount, quantity, location, and diversity of spawning habitats available to a population) rather than on characteristics occurring during other life stages. Because understanding the role of the estuary in affecting spatial structure and diversity is as important as understanding its effect on abundance and productivity, we consider these concepts and their application to salmon recovery efforts in greater detail below.

Spatial structure refers to the geographic distribution of individuals in the population and the processes that generate that distribution. The conceptual basis of spatial structure originates from principles of metapopulation dynamics (Hanski and Gilpin 1996), which describe how groups of populations interact with their habitat and with one another. Metapopulation principles suggest that persistence of a species in a variable environment will depend in part on the spatial distribution of suitable habitat, including the numbers, quality, and quantities of habitat patches occupied; patterns in the use of patches; when patches are occupied; when patches are available;

[2] C. Greene, NWFSC, Seattle, WA. Pers. commun., February 2004.

and the ability of members to colonize and use habitat patches. At any one time, there may be a wide variety of habitats that can be occupied by members of a population, although not all suitable habitats that are available will necessarily be occupied. The application of metapopulation principles to the conservation of salmonids has attracted considerable interest in recent years (e.g., McElhany et al. 2000, Rieman and Dunham 2000, Issak et al. 2003, Ruckelshaus et al. 2004).

Salmon populations clearly exhibit complex geographic structure that can be defined at multiple spatial scales. For example, at any moment, a population can be distributed across many thousands of square miles, ranging from the headwater spawning areas to Pacific Ocean feeding grounds (e.g., Healey 1991). Within one area, such as the estuary, multiple habitat types such as deep channels, mudflats, and emergent marshes can be simultaneously occupied by members of one population. Distributing members of a population through an array of habitats helps reduce the vulnerability of the population to shifts in environmental conditions (McElhany et al. 2000, Hilborn et al. 2003). There are, however, few studies directly linking geographic structure to observed patterns of estuarine use. Carl and Healey (1984) concluded that variations in migration behavior and estuarine use by Chinook salmon within the Nanaimo River basin were linked to different subpopulations associated with geographically distinct spawning areas.

Diversity consists of the variability in life history and discrete genetic traits exhibited by salmon. Diversity in salmon life histories exists along a continuum and includes individuals, subpopulations, populations, ESUs, and species. Along with spatial structure, phenotypic diversity helps buffer populations from environmental variability (e.g., Taylor 1990, Healey and Prince 1995, Hilborn et al. 2003). Life history diversity can be measured as variability in a wide variety of traits, including body size, fecundity and egg size, timing of life history events such as spawning, where spawning and rearing occurs, residence time in various habitats, habitat use, size at age, age at maturity, ocean distribution patterns, and physiological characteristics (Koski 1971, Healey and Heard 1984, Burger et al. 1985, Beachum and Murray 1987, Tallman and Healey 1991, Taylor 1990, 1991, Quinn and Unwin 1993, Roni and Quinn 1995, NRC 1996, Quinn et al. 2000, Waples et al. 2001, Hodgson and Quinn 2002, Beckman et al. 2003, Miller and Sadro 2003, Ramstad et al. 2003, Brannon et al. 2004). Variability in life histories can arise as a result of genetic variation, variation in environments the fish experience, or both; differentiating these is a considerable challenge. Thus some of the variability we see in life history patterns may be adaptive (i.e. genetically based) and reflect local adaptations that different salmon populations have evolved to cope with the specific conditions that they experience, including variability in estuarine habitats (Taylor 1991, Hansen and Jonsson 1991, Gharrett and Smoker 1993, Quinn et al. 2000). Other genetically based variations may not be adaptive, but instead may be due to random genetic drift (Stearns 1992).

One way to conceptualize life history diversity is as a set of alternate life history strategies or trajectories (we use these terms to refer to the same thing) that individual members of a salmon population can follow (Wissmar and Simenstad 1998). Each trajectory represents an approach to using the spawning, rearing, and migration habitats that are available to the fish in space and time. A variety of phenotypic differences (age at return, size at return, fecundity, and time spent in particular habitats) can exist between trajectories based on how habitats are used. From the perspective of the estuary, studies have demonstrated a broad range in the use of estuarine habitats between and within populations in such attributes as residence time, timing of

arrival in the estuary, habitat usage, and size of arrival in the estuary (e.g., Reimers 1973, Carl and Healey 1984, Levings et al. 1986, Quinn and Unwin 1993, Miller and Sadro 2003, Bottom et al. 2005, Bottom[3]).

A major factor affecting the number and quality of life history strategies (quality is defined as how successful the trajectory is at producing recruits) present within a population will be the distribution and quality of habitats that can potentially be used (NRC 1996). If the habitats do not exist because of either natural or anthropogenic factors, then population members cannot use them and distinct life history strategies can potentially be eliminated from the population. This can reduce viability of the population by diminishing productivity, spatial structure, and diversity. For a population to use diverse habitats, the habitats must be available and the right fish must be available to use these habitats (e.g., the appropriate genotype).

Although each member of a population is unique and has its own trajectory, these individual trajectories can be bundled or aggregated into a more limited number of general trajectories based on spatial and temporal patterns in use of habitats (e.g., Reimers 1973, Carl and Healey 1984, Beamer[4]). A variety of metrics associated with these general trajectories can then be used as measures of life history diversity including number of trajectories, condition of the trajectories (e.g., quality of habitats being used), distribution of members across trajectories, and success or survival of members using different strategies. In general, the abundance of members using some strategies will be greater than the abundance of members using other strategies within a population because those strategies are more successful under the prevailing environmental conditions. As conditions change, the distribution or proportion of members associated with each life history strategy can then shift. Over short time scales (e.g., annually), the distribution of strategies can vary in response to annual variability in such factors as flow, water temperature, and the occurrence of El Niño events. A sustained shift in conditions (e.g., climate shift, anthropogenic influences) potentially can produce more significant shifts in the distribution of life history traits (Hilborn et al. 2003).

The complex geographic distribution of members within populations and the alternate approaches to completing life cycles are not unique to salmon or anadromous species (Roughgarden et al. 1988, Sinclair 1988, Secor 1999, Able et al. 2003, King and MacFarlane 2003). As with salmon it is not clear in most cases, whether diversity is more facultative or genetically determined. The relative roles of genetics and the environment in inducing diversity will have a significant effect on any population's persistence in the face of changing environmental conditions. Within the Alagnak River, Alaska, Meka et al. (2003) found that rainbow trout *(Oncorhynchus mykiss)* exhibited three life history patterns based on their migratory movements within this river system. A similar diversity in movements within Yellowstone cutthroat trout *(Oncorhynchus clarki bouvieri)* was described by Gresswell et al. (1994). Although little genetic differentiation existed, they concluded that the range in variation in life history strategies within the cutthroat trout was an adequate basis for providing protection to each life history type. Curry et al. (2002) found a range of tactics related to the use of freshwater and estuarine habitats within one riverine brook trout population. Recent research has also revealed that striped bass *(Morone saxatilis)* exhibit a variety of life history approaches that

[3] D. Bottom, NWFSC, Newport Research Station, Newport , OR. Pers. commun., February 2004.
[4] E. Beamer, Skagit River System Cooperative, La Conner, WA. Pers. commun., January 2004.

can vary within and between populations in use of freshwater and estuarine landscapes (Secor and Piccoli 1996). Limburg (2001) found that there was differential mortality of American shad (*Alosa sapidissima*) based on fish size and age the fish emigrated from freshwater. Many populations of marine fish also exhibit complex approaches to how they distribute themselves in space and time that are similar to the tactics exhibited by anadromous species (e.g., Roughgarden et al. 1988, Able et al. 2003, King and McFarlane 2003).

In summary, estuaries are part of the continuum of habitats salmon use. Rather than serving as a bottleneck to production, estuarine habitats clearly contribute to the viability and persistence of salmon populations. They accomplish this in a number of ways. The amount of estuarine habitat that is accessible affects the abundance and productivity of a population. The distribution, connectivity, number, sizes, and shapes of estuarine habitat affects both the diversity and the spatial structure of a population. Attributes of estuarine habitats (e.g., temperature and salinity regimes, food web relationships) affect diversity and productivity of populations as life-stage specific survivals vary with habitat characteristics.

Analyzing Effects of Factors on Population Viability

In this section, we describe our approach to analyzing effects of estuarine factors on salmonid population viability. We first describe how we linked estuarine factors to their potential to affect the viability of each listed population. Because we had limited empirical information describing estuarine and plume habitat use by specific anadromous populations or ESUs in the Columbia River estuary and plume, we used an alternate approach. Specifically, effects of candidate factors were linked to viability of an ESU based on the life history type of each ESU and how a factor affected the distribution and quality of life history strategies associated with each life history type. As each ESU consists of an aggregate of populations, we can then infer responses of populations based on what we predict will occur for the ESU. Second, we describe which factors were included in our analyses and how they were selected. Finally, we describe the system we used to rate effects of each factor on viability of ESUs.

Defining Life History Type and Life History Strategy

We first defined the life history type of each ESU as either stream-type or ocean-type. The terms stream-type and ocean-type originated from Gilbert (1912) to discriminate Chinook salmon based on their length of stream residence. Based on banding patterns he observed on scales, Gilbert referred to stream-type fish as those fish having scales with a banding pattern consistent with a period of poor growth in winter in cold freshwater habitats. Ocean-type scales (he used the term sea-type) did not show this poor winter growth, indicating the fish moved into warmer, more productive marine waters before winter. Subsequently, Healey (1991) extended use of the terms to include both juvenile residence patterns and ocean distribution patterns. Healey (1991) proposed that ocean-types and stream-types were separate races that were independent and geographically isolated from one another except in the southern part of their range where they separated temporally in areas of sympatry. Recently, Healey's racial model explaining variability in Chinook salmon life history patterns at broad spatial scales has been challenged (Brannon et al. 2004, Waples et al. 2004).

We use the terms stream-type and ocean-type to separate ESUs into two groups based strictly on certain characteristics exhibited by juveniles during their first year of life, including how long they rear in freshwater, when they outmigrate, and how long they spend in estuarine habitats (Table 2). Populations are referred to as ocean-type if most of the members of the population migrate to sea early in their first year of life after spending only a short period (or no time) rearing in freshwater. A shorter period of freshwater rearing is usually correlated with more extensive use of estuarine and oceanic habitats. In contrast, most members of a stream-type population migrate to sea after rearing for at least a year in freshwater (Table 2). Thus ocean-type fish have a greater reliance on estuarine and ocean habitats during their first year of life, while stream-type salmon tend to depend on freshwater habitats during this same period. Differences in other life history characteristics can also occur as a function of juvenile life

Table 2. A summary of the juvenile characteristics of stream and ocean life history types as used in this report.

Stream-type fish	Ocean-type fish
Species	
Coho salmon	Coho salmon
Some Chinook populations	Some Chinook populations
Steelhead	Chum
Sockeye	Pink
Attributes	
Long period of freshwater rearing (>1 yr)	Short period of freshwater rearing
Shorter ocean residence	Longer ocean residence
Short period of estuarine residence	Longer period of estuarine residence
Larger size at time of estuarine entry	Smaller size at time of estuarine entry
Mostly use deeper, main channel estuarine habitats	Mostly use shallow water estuarine habitats, especially vegetated ones

history characteristics including differences in age and size at return and timing of return migrations (Healey 1991). However, there is not a simple relationship between these other life history characteristics and life history type. For example, while stream-type fish are often spring spawners and ocean-type fish are generally fall spawners, there are numerous exceptions (Brannon et al. 2004, Waples et al. 2004).

An ESU was classified as stream type if the majority of populations within that ESU fit the stream-type life history model; an ESU was classified as ocean type if the majority of populations fit that life history type. Information documented in the following species status reviews was used to classify the populations and ESUs: Myers et al. (1998) for Chinook salmon, Johnson et al. (1997) for chum salmon, and Busby et al. (1996) for sockeye and steelhead.

Individual members within a population exhibit a variety of alternative spatial and temporal trajectories, or life history strategies, for using available habitat. We defined alternative life history strategies based solely on the size at estuarine entry and arrival time in the estuary. Size at entrance into the estuary can be used to classify life history strategy because there is a linkage between fish size, habitat use, and residence time (Healey 1980, 1982, Levy and Northcote 1981, 1982, Simenstad et al. 1982, Levings et al. 1986, Tschplanski 1987, Miller and Sadro 2003). In general, residence time in the estuary decreases as the size of the fish entering the estuary increases (with the exception of pink salmon). In addition, juvenile salmon are generally distributed based on water depth, with the depth of the water occupied by the fish increasing as the size of the fish increases (McCabe et al. 1986). Larger fish can result from growth either in estuarine or freshwater habitats. There is not necessarily a continuous relationship between habitat occupied and fish size but rather there may be transitional or

threshold sizes where most fish shift from use of one habitat type to another. For example, Simenstad et al. (1980) suggested that juvenile chum shifted from shallow littoral habitats to more offshore habitats in Puget Sound at a size of about 50 mm.

The time the fish arrive in the estuary also varies within a general size class of individuals (Carl and Healey 1984, Bottom et al. 2005). Because available resources and habitats can be different depending on when a fish arrives in the estuary, arrival timing represents a reasonable way to define how the fish use habitats. The wide range in variability in size at estuarine entry and time of entry that can occur is illustrated by Figure 2 from Bottom et al. (2005). In this analysis, Bottom et al. (2005) classified historical early life history strategies for juvenile salmon recovered in the Columbia River estuary based on size at entry, time of entry, freshwater life history (where and how long the fish reared in freshwater), and estuarine growth data generated from scale pattern analyses performed by Rich (1920). For example, under historical conditions, fry (fish < 60 mm at estuarine entry) were found in the estuary nearly year round, while yearlings were present from February to June. The source populations were not identified in these analyses, but it is reasonable to assume that many ESUs contributed to the patterns historically observed in the Columbia River estuary.

Based primarily on size at arrival in the estuary and time of estuarine entry data derived from Burke's (2005) reanalysis of Rich's scale information, we defined six general life history strategies that used the estuary historically (Table 3): 1) early fry, 2) late fry, 3) early fingerling, 4) late fingerling, 5) subyearling, and 6) yearling. Fry were defined as fish that enter the estuary at a size less than 60 mm, with early fry entering in approximately March and April and late fry from May to June. Fingerlings were identified as fish that enter the estuary at a larger size than fry, which implies there was some period of freshwater rearing; fingerlings have yet to begin the physiological transition associated with smolting. Fingerlings rear in the estuary for some period, with early fingerlings entering between January and July and late fingerlings from August to December. Subyearlings are fish that rear for less than a year in freshwater, rear little in the estuary, and smolt as they outmigrate during their first year of life. They reside in the estuary for less time than fry or fingerling salmon. Yearlings rear for at least one year in freshwater and then emigrate; these fish generally spend less time in the estuary than fry or fingerlings.

Although any one population can potentially produce all strategies, some strategies will be more abundant or dominant than others within a population. In general, yearlings will tend to be the dominant life history strategy in stream-type populations, while nonyearlings will be most abundant in ocean-type populations. The distribution or proportion of members within a population associated with each life history strategy will depend on the environmental conditions the fish are experiencing (e.g., ocean conditions, freshwater spawning habitat, and predator populations). The distribution of members within different strategies can vary in response to climate changes, flow, water temperature, and ocean conditions.

Considering the dramatic changes that have occurred over the last 100 plus years in climate, estuarine habitats, ocean conditions, and the freshwater spawning and rearing habitats that produce the source populations, it seems reasonable to assume that these changes have altered the distribution of life history strategies within populations and therefore within ESUs. This change is suggested by comparing current and historical use of the estuary by different

Table 3. Some general attributes of life history strategies associated with Columbia River anadromous salmon populations based upon historical use of the system. Information from D. Bottom, NWFSC, and J. Burke, University of Washington School of Aquatic and Fishery Sciences, was used to develop this table. All values should be considered general estimates.

Life history strategy	Attributes
Early fry	Time of estuarine entry: March–April Size at estuarine entry: <50 mm Estuarine residence time: 0–40 days Freshwater rearing: 0–60 days
Late fry	Time of estuarine entry: May–June, present through September Size at estuarine entry: <60 mm Estuarine residence time: < 50 days Freshwater rearing: 20–60 days
Early fingerling	Time of estuarine entry: April–May Size at estuarine entry: 60–100 mm Estuarine residence time: <50 days Freshwater rearing: 60–120 days
Late fingerling	Time of estuarine entry: June–October, present through winter Size at estuarine entry: 60–130 mm Estuarine residence time: 0–80 days Freshwater rearing: 50–180 days
Subyearling (smolt)	Time of estuarine entry: April–October Size at estuarine entry: 70–130 mm Estuarine residence time: <20 days Freshwater rearing: 20–180 days
Yearling	Time of estuarine entry: February–May Size at estuarine entry: >100 mm Estuarine residence time: <20 days Freshwater rearing: >1 year

strategies of Chinook salmon (Figure 2). For the estuary as a whole, all life history strategies were evident for longer periods of time throughout the year (Rich 1920); clearly, the current use of the estuary is more limited now than in the past. We examined possible changes in expression of different life history strategies for each ESU between historical and current conditions. Such a change analysis is restricted by the limited information on the distribution of life history strategies under either current or historical conditions for specific ESUs or populations. We defined the mix of life history strategies that we believe is likely being expressed by each ESU, under current conditions based on a variety of information sources including the life history type of that ESU, origin, unpublished data from the ongoing studies of Columbia River estuary (Bottom unpubl. data), and status reviews. We then extrapolated the likely mix of life history strategies historically employed by each ESU, using such information as Figure 2, and predicted

how different types of changes affecting each ESU would have impacted each life history strategy (Table 4). The changes in distribution of life history strategies described in Table 4 should be considered hypotheses.

Selection of Estuarine Factors for Analysis

To facilitate recovery of endangered salmon stocks in the Columbia River basin, factors that currently act to suppress an increase in their viability need to be identified. If the factors are appropriately and correctly pinpointed and can be manipulated, it is logical to conclude that reducing their affect should improve the recovery potential of targeted populations. Further, incorporating the influence of a factor's impact on recovery of salmon populations should improve policy and management decisions.

We recognize that identifying single habitat factor solutions to salmon survival problems in isolation has not been historically effective. A growing body of evidence suggests that a broader scale view of ecosystem restoration that focuses on how alteration to landscape processes and ecosystem attributes affects salmon via habitat changes is more likely to succeed (NRC 1996, Beechie and Bolton 1999, Stouder et al. 1999, Roni et al. 2002, Beechie et al. 2003a, 2003b). Identification of limiting factors in the estuary represents a logical first step that needs to be incorporated into a broad, landscape-scale assessment of strategies to improve the recovery potential for endangered salmon populations. Our goal here is to consider the effects of several estuarine factors on recovery of listed anadromous salmonids.

The major estuarine related factors that we identified that can potentially affect salmonid population viability in the Columbia River estuary are climate and climate change (which can control other factors): water flow; access to and quality of habitats; sediment; salinity; temperature; toxics/contaminants; predators such as Caspian terns (*Sterna caspia*), cormorants (*Phalacrocorax auritus*), marine mammals, and northern pikeminnow (*Ptychocheilus oregonensis*); hatchery practices; and harvest practices. Although it would be useful to evaluate the role of each of these factors, we selected water flow, habitat, Caspian tern predation, and contaminants for detailed analysis. These four were selected based on four criteria:

1. Was there a significant change in the factor from historical condition?
2. Could the factor potentially affect population viability?
3. Was quantitative data available that could be used to analyze effects of the factor?
4. Could the factor be linked to hydropower operations in the Columbia River basin?

We relied primarily on the first three criteria and did not use the fourth to exclude any factor.

We wish to emphasize that factors were not selected based on whether or not we believed they had a significant affect on salmonid population viability. Some factors that were not selected for consideration in this report may have a significant affect on viability. For example, we expect that water temperatures have warmed from historical levels, which could exclude some habitat from use by juveniles during part of the year and affect metabolic processes of both salmon and their predators. These changes in water temperature could alter growth and survival. A major purpose in our evaluation was to lay out a framework for future consideration of other

Table 4. Linkage between anadromous salmonid ESU, life history type (ocean-type or stream-type), and dominant life history strategies of juvenile salmon in the Columbia River. We estimated general contribution to the outmigrant population of each life history strategy as Abundant (>50%), Medium (10–50%), Rare (1–9%), or Absent (<1%) listed for each ESU under historical (early 1900s) [H] and current conditions.[C] We made these estimates using a variety of data sources and our judgment about how the various changes occurring in the system would have affected each strategy within each ESU.

		Life history strategy					
ESU	**Life history type**	Early fry	Late fry	Early fingerling	Late fingerling	Subyearling	Yearling
Columbia River chum salmon	Ocean	Abundant [H] Abundant [C]	Abundant [H] Abundant [C]	Absent [H] Absent [C]	Absent [H] Absent [C]	Absent [H] Absent [C]	Absent [H] Absent [C]
Snake River sockeye salmon	Stream	Absent [H] Absent [C]	Absent [H] Absent [C]	Absent [H] Absent [C]	Absent [H] Absent [C]	Rare [H] Rare [C]	Abundant [H] Abundant [C]
Lower Columbia River coho salmon	Stream	Rare [H] Absent [C]	Rare [H] Absent [C]	Rare [H] Absent [C]	Rare [H] Absent [C]	Rare [H] Rare [C]	Abundant [H] Abundant [C]
Upper Columbia River steelhead	Stream	Absent [H] Absent [C]	Absent [H] Absent [C]	Absent [H] Absent [C]	Absent [H] Absent [C]	Rare [H] Absent [C]	Abundant [H] Abundant [C]
Snake River steelhead	Stream	Absent [H] Absent [C]	Absent [H] Absent [C]	Absent [H] Absent [C]	Absent [H] Absent [C]	Rare [H] Absent [C]	Abundant [H] Abundant [C]
Lower Columbia River steelhead	Stream	Absent [H] Absent [C]	Absent [H] Absent [C]	Rare [H] Absent [C]	Rare [H] Absent [C]	Medium [H] Rare [C]	Abundant [H] Abundant [C]
Middle Columbia River steelhead	Stream	Absent [H] Absent [C]	Absent [H] Absent [C]	Rare [H] Absent [C]	Rare [H] Absent [C]	Medium [H] Rare [C]	Abundant [H] Abundant [C]
Upper Willamette River steelhead	Stream	Absent [H] Absent [C]	Absent [H] Absent [C]	Absent [H] Absent [C]	Absent [H] Absent [C]	Rare [H] Absent [C]	Abundant [H] Abundant [C]

Table 4 continued. Linkage between anadromous salmonid ESU, life history type (ocean-type or stream-type), and dominant life history strategies of juvenile salmon in the Columbia River. We estimated general contribution to the outmigrant population of each life history strategy as Abundant (>50%), Medium (10–50%), Rare (1–9%), or Absent (<1%) listed for each ESU under historical (early 1900s) [H] and current conditions.[C] We made these estimates using a variety of data sources and our judgment about how the various changes occurring in the system would have affected each strategy within each ESU.

		Life history strategy					
ESU	**Life history type**	Early fry	Late fry	Early fingerling	Late fingerling	Subyearling	Yearling
Snake River fall Chinook salmon	Ocean	Absent [H] Absent [C]	Absent [H] Absent [C]	Medium [H] Rare [C]	Medium [H] Rare [C]	Abundant [H] Abundant [C]	Rare [H] Medium [C]
Upper Willamette River Chinook salmon	Ocean	Rare [H] Absent [C]	Rare [H] Absent [C]	Medium [H] Rare [C]	Medium [H] Rare [C]	Rare [H] Medium [C]	Abundant [H] Abundant [C]
Lower Columbia River fall Chinook salmon	Ocean	Medium [H] Rare [C]	Medium [H] Rare [C]	Medium [H] Rare [C]	Medium [H] Rare [C]	Medium [H] Abundant [C]	Rare [H] Rare [C]
Upper Columbia River spring Chinook salmon	Stream	Absent [H] Absent [C]	Absent [H] Absent [C]	Rare [H] Absent [C]	Rare [H] Absent [C]	Rare [H] Rare [C]	Abundant [H] Abundant [C]
Snake River spring/summer Chinook salmon	Stream	Absent [H] Absent [C]	Absent [H] Absent [C]	Rare [H] Absent [C]	Rare [H] Absent [C]	Rare [H] Rare [C]	Abundant [H] Abundant [C]

factors that may affect juvenile salmon use and that could be used as more comprehensive information becomes available.

For each factor, we considered how it could affect population viability based on available data and analyses. We then developed a series of hypotheses or principles about each factor that helped guide how we rated their relative importance for each ESU. In addition, we assessed changes in each factor from historical conditions. Such a comparison between historical and current conditions is a useful way to help identify causes and mechanisms of ecosystem change (e.g., Borde et al. 2003, Beechie et al. 2003b, Collins et al. 2003).

Analyzing and Rating the Relative Importance of Estuarine Factors

To rate the importance of each factor, we developed a simple rating system that ranked each factor as having a high, medium, or low ability to improve the status of anadromous salmon populations. We defined improvement in population status to mean improvement in population viability (McElhany et al. 2000). We drew inferences about how a factor affects an ESU based on the life history type of that ESU, how we believed the factor would affect the life history strategies that characterized that life history type, and the hypotheses and principles developed from the overviews of each factor. The limiting factors for all stream-type ESUs were ranked similarly while those for ocean-type ESUs were ranked similarly. Ratings were developed by considering each factor relative to other estuarine factors within an ESU; ratings were not considered relative to other nonestuarine factors such as tributary habitat.

The rating system consisted of two levels. The level 1 screen evaluated if the factor was likely a concern for an ESU based on its affects on VSP and changes in that factor from historical conditions. The level 2 screens asked how the factor affected an ESU based on where the affects occurred and the life history strategies affected.

Level 1: Is the Factor Likely a Concern for the ESU?

What is the affect on each VSP parameter?

Each factor will have some affect on each VSP parameter. We assumed, however, that if the factor affected large numbers of individuals in the ESU and individuals associated with multiple life history strategies (again, relative to other factors) that there was a significant affect on abundance and productivity. If a factor primarily affected only one or two particular life history strategies or specific habitat types more than others, we assumed the primary affect of the factor was on spatial structure and diversity. Because most populations in threatened or endangered status are at low levels of abundance, we reasoned that the abundance levels of these depressed populations needed to be increased as soon as possible. Therefore, we doubled the score if the factor affected abundance and productivity.

Has the factor changed from historic conditions and what it is the likelihood that it could be improved relative to the other factors?

We considered whether each factor had changed significantly from historical conditions. Because we intentionally selected factors that we believed had changed significantly from

historical conditions, this screen did not differentiate much between factors. We also considered from a practical perspective how much change in each factor was possible. A factor could be significantly changed from historical levels but relatively difficult to change relative to other estuarine factors.

Level 2: How Does the Factor Affect the ESU?

Does the factor have a significant affect on the abundance of the dominant life history strategy?

For the dominant life history strategy, we asked how the factor affected the abundance of juveniles of that life history type in shallow water habitats (upstream of the river's mouth), deepwater habitats (upstream of the river's mouth), and plume habitats. We only considered these three areas because available information indicates that use of habitats in the plume and confined portion of the estuary (river mouth to Bonneville Dam) is quite different. Thus separation of the estuary into these two large zones was warranted. Within the zone from Bonneville Dam to the river's mouth, we also differentiated use of shallow, low velocity habitats from medium and deep, higher velocity channel habitats because this was also consistent with available information. Studies indicate that smaller juveniles more extensively use shallow, low velocity habitats (e.g., swamps, emergent marshes, and shallow flats) than medium and deep, higher velocity channel habitats; the opposite pattern exists for larger size classes such as yearlings (Healey 1980, 1982, Levy and Northcote 1981, 1982, Simenstad et al. 1982, Levings et al. 1986, Miller and Sadro 2003).

For the dominant life history strategy, does the factor affect habitat quality, quantity, and opportunity?

For the dominant life history strategy, we asked what type of affect the factor had in shallow water (upstream of the river's mouth), deepwater (upstream of the river's mouth), and plume habitats. We considered effects of the factor on habitat quantity, quality, and opportunity. The concepts of opportunity and quality (or capacity) were proposed by Simenstad and Cordell (2000) and adopted by Bottom et al. (2005) for the Columbia River estuary.

Opportunity attributes relate to the accessibility of habitat to juvenile salmon. In general, opportunity metrics are largely physical and chemical in nature such as tidal elevation, temperature, and location of habitat. For example, extreme high temperatures and diminished flows can constrain accessibility of shallow water habitat. Capacity measures primarily relate to the biotic and ecological functions (i.e., acquiring food and avoiding being eaten) of habitat. Capacity metrics must be considered within the context of the species and life stage using the habitat, and the location of that habitat within the landscape. In addition to capacity and opportunity, we also included quantity of habitat as a separate metric. For toxics, we rated effects separately in shallow water and deepwater estuarine habitat for waterborne and sediment-borne contaminants. For example, if there were risks to the main life history type from both types of contaminants in shallow water, then the score would double.

Each of the four questions listed above was evaluated for each factor and each ESU based on whether the ESU was classified as an ocean or stream life history type. Each cell in a matrix

was either scored as a yes (+1) or no (0) with two exceptions: 1) abundance and productivity which were given a +2 score, and 2) toxics in deep and shallow water which each could be scored a +2 if there was effects from both waterborne and sediment-associated toxics. This affected the maximum possible score that could be assigned to a factor. For flow, habitat, and predation, the maximum possible score was 20, whereas the maximum possible toxics score was 28. The final rating was computed as the ratio between the assigned score and maximum possible score; a ratio of >0.66 was assigned a high ranking, 0.34–0.66 a medium ranking, and <0.34 a low ranking.

Analyses of the Effects of Estuarine Factors on Columbia River Basin Salmonids

Water Flow

Water, interacting with the land, creates and maintains the mosaic of estuarine habitats that juvenile salmon occupy. The estuarine habitat features to which salmon have adapted are largely the result of riverine and tidal processes and the physical characteristics of the watershed. The major geologic feature affecting flows through the basin is the Cascade mountain range, which divides the Columbia River drainage basin into interior and western subbasins. The moist and relatively warm western subbasin contains only about 8% of the total surface area of the 660,480-km^2 basin, but contributes almost one quarter of the total river flow (Orem 1968). Most of the western subbasin is at too low an elevation to accumulate a large seasonal snow pack. Thus the highest flows are observed during and after winter storms, between December and March. In contrast, most of the flow in the interior subbasin occurs as the result of the seasonal snow pack melt between April and July. Much of the interior subbasin is relatively arid, but its Canadian component experiences heavy winter snowfall and plays a major role in spring freshet flows.

Effects of Climate on Flow

Natural variations in Columbia River flows associated with both short and long term fluctuations in climate have a significant affect on amount and timing of water delivered to the estuary. These variations directly affect habitat conditions in the estuary, and help determine what areas are wetted and potentially accessible to juvenile salmon and how estuarine salinity gradients vary. Climate-induced variations in Columbia River flow occur on time scales from months to centuries (Chatters and Hoover 1986, 1992). One example of a longer term climate effect is the Pacific Decadel Oscillation, commonly known as the PDO (Francis and Hare 1994, Mantua et al. 1997), which alternates between cold and warm phases at approximately 30-year time scales. During the cold phase, more rainfall is typical in the Pacific Northwest, whereas in the warm phase, less rainfall occurs. The cold phase of the PDO (e.g., the 1945–1976 period) was regarded as benefiting salmonid production in the Pacific Northwest, while being less favorable for salmon originating in northern British Columbia and Alaska (Hare et al. 1999). The opposite circumstance prevails during the warm phase, characteristic of the recent period between 1977 to about 1998, when listing of salmon in the basin occurred. Another cold, wet phase seems to have commenced about 1998 (Peterson and Schwing 2003). PDO-related fluctuations in salmonid survival have been linked to the degree of density stratification of the coastal ocean (Gargett 1997), but they are also likely influenced by conditions within the river and estuary (e.g., salinity, turbidity, and river flow).

Another climate related feature is the El Niño-Southern Oscillation (ENSO; typically 3–7 years in duration) cycles (Redmond and Koch 1991, Kahya and Dracup 1993, Dracup and Kahya

1994, Gershunov et al. 1999, Jay 2001). ENSO cycles are shorter in duration compared to the PDO cycle, typically amplifying conditions associated with the cold or warm phase of the PDO. El Niño winters in the Pacific Northwest often bring high sea level, warm air temperature, low precipitation, low snowpack, and weak subsequent spring freshet flows (Kahya and Dracup 1993, Dracup and Kathya 1994). La Niña winters (the contrast to El Niño) typically exhibit an opposing climate and hydrological response. As a consequence, the annual average flows of the Columbia and the Willamette rivers during years with a strong El Niño winter are 91% and 92% of the long-term annual average, while in case of strong La Niña winters, they are 110% and 111%, respectively. El Niño effects are intensified during a warm-PDO phase, while those of La Niña are enhanced during a cold-PDO phase (Gershunov et al. 1999). Conversely, El Niño effects are suppressed during the cold-PDO phase, as are those of La Niña during the warm-PDO phase (Jay 2001).

The Columbia River basin's climate response is conditioned by its position between 41°30' and 54°40'N lat., within a latitudinal band of strong response to the ENSO cycle and to the PDO (Mantua et al. 1997). However, the affects of climate on flow vary considerably depending on location within the basin. While the river flow per unit area is much larger in the western than in the interior subbasin, there are only modest variations across the basin in response to ENSO or PDO forcing. Still, the relatively large north-south extent of the basin brings about important differences in flow seasonality—the incidence of winter floods and timing of spring snowmelt—even within the interior subbasin.

What Changes Have Occurred in Flow Attributes

Changes in flow attributes, such as when and how much water arrives in the estuary, are an integral measure of alterations in a river system. In a recent analysis and review, Jay (2005) provided a detailed estimate of changes in flows in the Columbia River for the past 100 years, thereby providing an accounting of flow conditions during the historical and current period. One measure of hydrological change is the overall quantity of water delivered to the estuary. Jay concluded that there has been approximately a 16.4% reduction in river flow during the last 100 years. He evaluated the contribution of climate and human perturbation on the observed flow and concluded that approximately half of this change was due to climate (less rainfall) and half to human activities (e.g., water withdrawal for irrigation). In addition, a small percentage of the decrease was assigned to a combination of uncertainty (error) and evaporation from the impoundment of water in reservoirs due to increased surface area in the basin. Jay's conclusions were based on the record of observed flows for the past 100 years and an estimated adjusted flow provided by the U.S. Geological Survey (USGS) to account for reservoir manipulations; this was used to estimate the virgin river flow (flow unadulterated due to hydropower operations and irrigation removal) from approximately 100 years ago (Figure 6).

Reductions in the total amount of water (i.e., annual average flow) are only a small part of the total hydrological changes that have occurred in the Columbia River basin. Seasonal changes, particularly those involving the timing and magnitude of the spring freshet, have been much larger than changes in annual average flow. Spring freshets are extremely important for juvenile salmonids in that high flows (especially overbank flows) provide habitat, transport fish downstream, limit predation by increasing turbidity, and maintain favorable water temperatures during the spring and early summer. Organic matter supplied by the river during the freshet

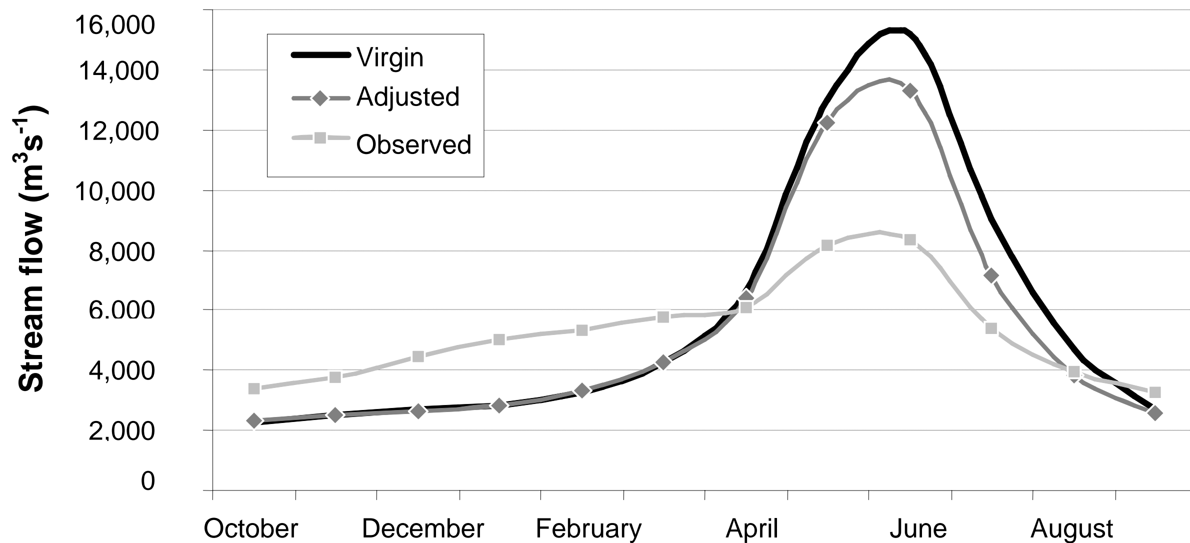

Figure 6. Comparison of the monthly averaged Columbia River eastern subbasin virgin, adjusted, and observed river-flow (cubic meters per second) estimates from 1970 to 1999. Flow regulation and irrigation depletion decreased spring and summer flows (May to August), while fall and winter flows (September to March) increased. (Reprinted from Bottom et al. 2005.)

season is also a major factor maintaining a detritus-based food web, centered in the estuarine turbidity maximum (ETM).

Very large freshets before modern flow regulation (i.e., before ≈1970) lasted 30–60 days, with the sharpness of the peak largely governed by the relative timing of snowmelt throughout the basin. Flows in the Columbia River interior subbasin (the flow measured at the The Dalles) are primarily driven by spring snowmelt, although there are rain-on-snow freshets in some winters. Before 1900, the highest flows typically occurred during May–July (Figure 7).

The timing of the maximum spring freshet flow has also changed (Figure 8). Maximum daily spring freshet flow now typically occurs at about water-year Day 242 (29 May), whereas maximum flow occurred in the 19th century at about water-year Day 256 (12 June), a change of about two weeks. In terms of the phase of the annual flow fluctuation, the freshet is about a month earlier. Part of this change is due to climate warming, but a component is also due to pre-release of water for flood control before the spring freshet. Irrigation withdrawal usually peaks in June, which tends to further curtail the freshet.

Another change in water flow, significant to salmon, is the occurrence of overbank flows. The historical bankfull flow level was an estimated 18,000 m^3s^{-1} for the main stem below Vancouver (Jay 2005). Modern bankfull level is set by the standard project flood level of approximately 24,000 m^3s^{-1} for the lower river. According to Jay (2005), some overbank flow occurred in many years before 1900, both in winter and spring (Figure 9), whereas substantial overbank flow (above 24,000 m^3s^{-1}) is now rare, with significant events occurring only five times during the last half century. Historical bankfull levels of 18,000 m^3s^{-1} are now rarely exceeded due to the combined effects of flood control measures and irrigation depletion. The season when

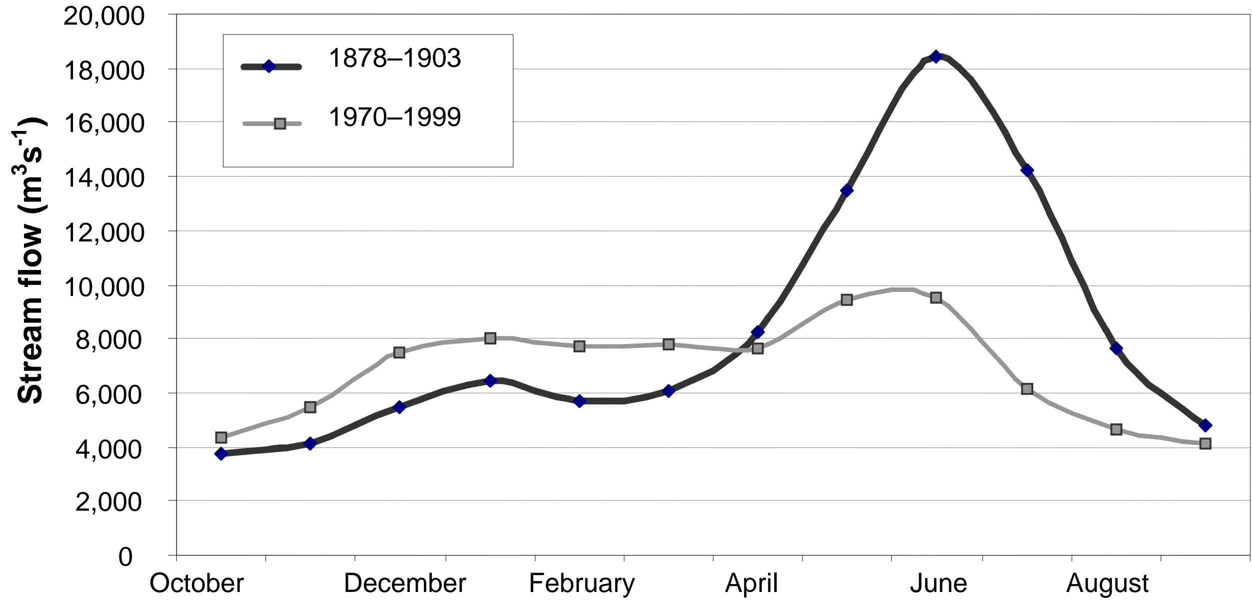

Figure 7. Changes in the annual Columbia River flow cycle at Beaver Army Terminal, near Quincy, Oregon, 1878–1903 versus 1970–1999. (Reprinted from Bottom et al. 2005.)

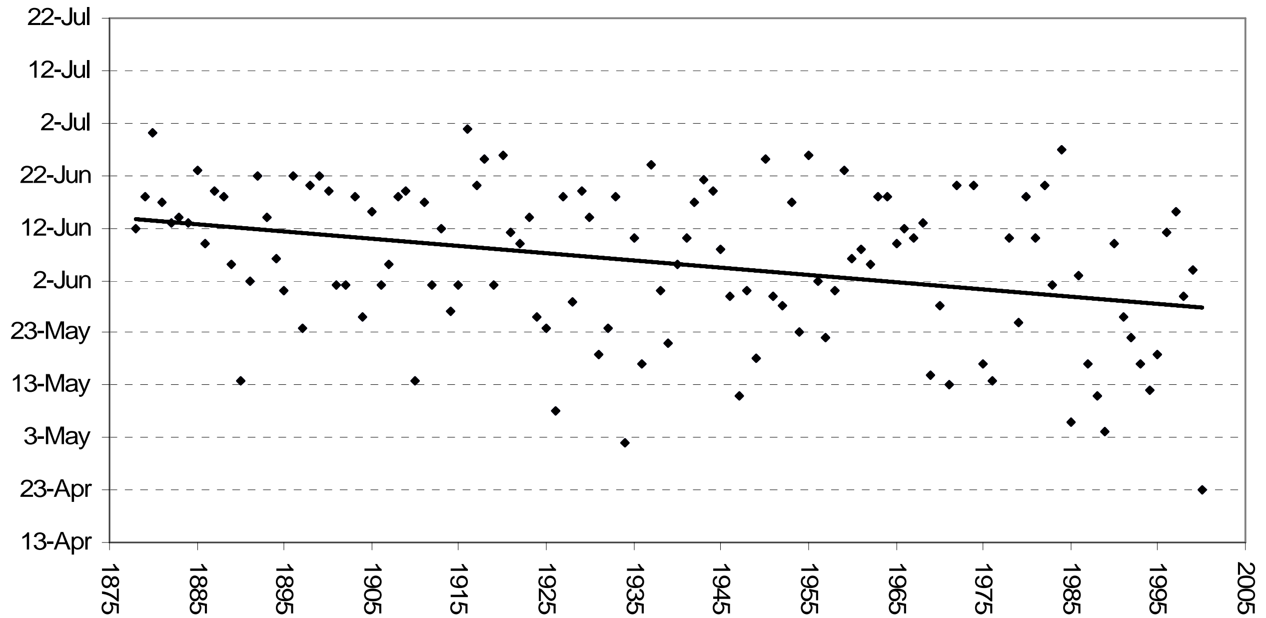

Figure 8. Peak freshet day versus year suggests that the freshet is now about two weeks earlier than in the 19th century in the Columbia River basin. (Reprinted from Bottom et al. 2005.)

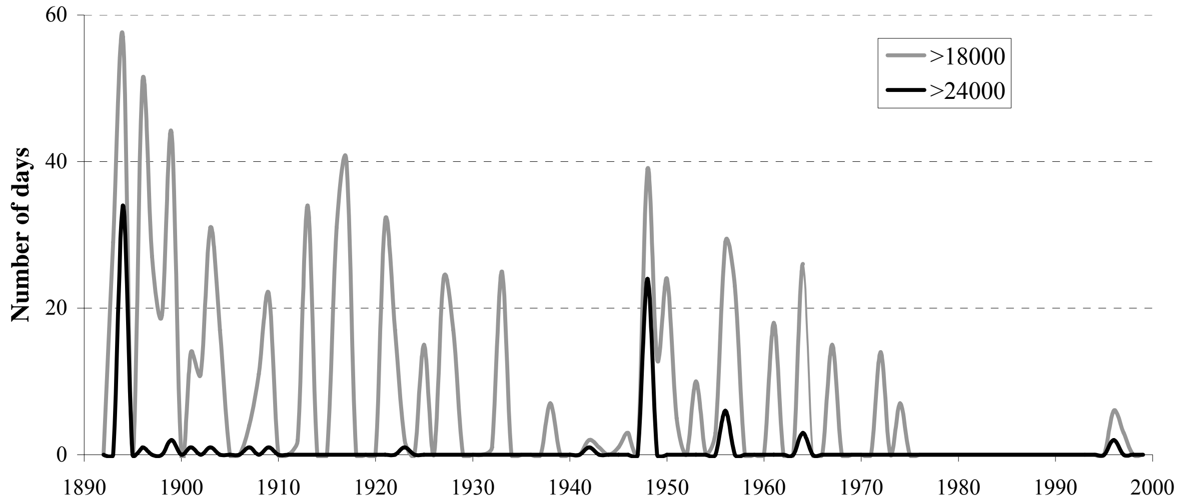

Figure 9. The incidence of flows above 18,000 m^3s^{-1} (the pre-1900 estimated bankfull flow level) and above 24,000 m^3s^{-1} (the present bankfull flow level). The present bankfull flow level has been exceeded only five times (twice in 1956) in four years since 1948. (Reprinted from Bottom et al. 2005.)

overbank flow typically occurs has also shifted from spring to winter, because western subbasin winter floods (not interior subbasin spring freshets) are now the major source of such flows (Jay 2005).

Factors Causing Changes in Flow Attributes

Potentially, flow changes (e.g., decreased spring freshets) can be a result of climate change, flow regulation, and water withdrawal. Jay (2005) apportioned the timing and magnitude of the freshet change to these three factors and found that flow regulation is clearly the source of the largest reduction in spring flow. The total reduction in freshet season (May through July) mean flow due to climate change, irrigation depletion, and flow regulation is 5,870 m^3s^{-1} or 43% of the virgin flow for this period. Overall the present freshet season flow decrease due to flow regulation was an estimated 33.1% (a reduction of 31.6% for May, 32.4% for June, and 19.8% for July, respectively). Jay found that the flow decrease in the freshet period resulting from climate was 5.6%. Similarly, the present decrease in freshet season flow due to water withdrawal was an estimated 10.5% (a reduction of 5.7% for May, 12.5% for June, and 20.8% for July, respectively). The January through July virgin flow average for 1879–1899 was 8,050 m^3s^{-1}, while for 1945–1989 it was 7,850 m^3s^{-1}, a decrease of only 2.5%. Thus most of the loss of freshet flow represents flow that now occurs during other time periods.

Climate was found to be a secondary factor in the incidence of overbank flow (Jay 2005). Overbank flow events were more common during the cold-PDO phase (1945–1977) than during the preceding warm-PDO phase (1921–1944), even though the degree of flow regulation and irrigation depletion grew over time (Figure 10). Jay concluded flood protection, diking, flow regulation, and water withdrawal largely eliminated climate's influence on overbank flow.