Salmon at River's End:

The Role of the Estuary in the Decline and Recovery of Columbia River Salmon

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Willis Horton Rich
1885-1972

       To Willis Rich, whose career included service to the U.S. Bureau of Fisheries, U.S. Fish and Wildlife Service, and Oregon Fish Commission. Willis Rich also served as Full Professor at Stanford University. He pioneered the study of Pacific salmon migrations and life cycles. He was among the first to recognize that the return of salmon to their natal streams creates a complex structure of isolated, self-sustaining populations within species. From this understanding, Rich proposed a revolutionary approach to salmon management based on the conservation of local populations within their native habitats.

EXECUTIVE SUMMARY

To evaluate the capacity of the estuary to support salmon, including the effects of flow regulation on this capacity, the following six analyses were completed and the results interpreted based on the relationships between habitat and salmon life histories described below:

1. A review of the historical development of Columbia River and estuary relative to changes in its salmon populations;

2. An analysis of alternative conceptual frameworks for evaluating estuarine habitat conditions for Columbia River salmon;

3. An assessment of the effects of climate and the hydropower system on river flow and sediment transport within the context of regional climate variability and change;

4. A test of the ability of a hydrodynamic model to simulate the effects of flow regulation and bathymetric change on the opportunity for subyearling chinook to access preferred estuarine habitat;

5. An evaluation of biological and bioenergetic factors that may affect the capacity of available estuarine habitats to support salmon;

6. An evaluation of population structure, life-history diversity, and performance of juvenile chinook in the estuary at various periods through the development of the river and estuary.

Principal findings from each of these analyses are summarized below.

1. Estuarine Development History and Salmon Decline

Industrial development of the Columbia River and its estuary and declines in salmon populations are well documented. The effects of intensive harvest were apparent throughout the Columbia River Basin by 1911, just as dam construction and irrigation diversion were beginning, and alterations to the estuary for navigation were unfolding. Increased salmon conservation measures and management initiatives, however, coincided with the decline in freshwater habitat, regulation and diversion of river flow, loss and degradation of estuarine habitat.

Installation of hydroelectric and irrigation diversion dams without providing for fish passage reduced salmon spawning and rearing habitat by 55%. Today, 23 mainstem and over 300 tributary dams regulate the flow of the Columbia to the sea. Through this development history, the Columbia River became progressively channelized and detached from its floodplain.

Approximately 65% of the tidal marsh and swamp habitat below Jones Beach had been diked or filled by the middle of the 20th century. The loss of these habitats between Jones Beach and Bonneville Dam was likely greater but has not been quantified. Many other activities have degraded habitat throughout the estuary including upland logging

and agriculture, shoreline armoring, construction of over-water structures, removal of large wood, and channel deepening and widening.

In order to compensate for habitat losses and salmon decline, resource managers developed intensive hatchery programs that substituted concentrated releases of a few artificially produced stocks for the more diverse populations and life-history types that were formerly distributed throughout the watershed. More than 95% of the adult coho, 70% of the spring chinook, about 80% of the summer chinook, more than 50% of the fall chinook salmon, and about 70% of the steelhead now returning to the Columbia River originate from the more than 80 hatcheries in the watershed. As a consequence of these and other factors addressed in this analysis, historical salmon returns to the Columbia River of 11 to 16 million fish annually have now declined to fewer than 12% of predevelopment levels.

2. A Conceptual Framework for Evaluating Estuarine Habitat Conditions

Decline of Columbia River salmon populations has been attributed to numerous factors, including overfishing and harvest mismanagement, hatchery overproduction, changes to the river and watershed, pollution, predators, exotic species, and fluctuations in oceanic and climatic conditions. While each of these individual factors has been implicated as independent "bottlenecks" to salmon recovery, it is the interaction of multiple factors throughout the life history of salmon that determines their reproductive success. This understanding is critical for the conservation and recovery of Columbia River salmon.

The notion of independent limiting factors to salmon production stems from a traditional agricultural approach to resource management. From this perspective, the estuary was viewed as a hazardous environment where numerous predators or competitors must be controlled to ensure efficient salmon production. This perspective provided little information about the estuarine habitats that salmon need or the processes that link freshwater, estuarine, and marine habitats. A fundamental impediment to salmon and estuary recovery, therefore, is the lack of an explicit conceptual framework to explain the evolutionary and ecological requirements of diverse salmon populations.

In this assessment we adopted a conceptual framework that is based on the complex geography of local, self-perpetuating populations of salmon. A crucial assumption of our analysis was that *resilience of Columbia River salmon to natural environmental variability is embodied in population and life-history diversity, which maximizes the ability of populations to exploit estuarine rearing habitats*. This assumption recognizes variation in rearing behavior (phenotypic diversity) as the result of diverse salmon genotypes interacting with unique habitat features.

These interactions result in a variety of alternative behavioral "solutions," for salmon to successfully complete their life cycles such as variation in timing and age of migration, alternating periods of residence in the river and estuary, and variation in size at ocean entry. The total productive capacity of the Columbia River Basin for salmon is therefore a function of all combinations of genotype and habitat that allow for the full expression of salmon rearing and migration behaviors, including diverse life histories in the estuary.

This conceptual framework suggests that the productive capacity of the Columbia River estuary can be affected in any one or all of the following ways:

- By removing or degrading estuarine habitats that salmon require to express the full diversity of potential rearing behaviors;

- By altering population structures and genetic characteristics in component populations of the basin that converge in the estuary en route to the ocean; or

- By directly altering the phenotypic behavior of salmon through hatchery releases, transportation of fish, etc., whether or not the underlying genetic structure of populations is affected.

In this evaluation, an effort was made to distinguish the role of the Columbia River hydropower system from other factors that influence the salmon rearing capacity of the estuary, including phenotypic or genetic effects that can determine whether or not salmon fully utilize this capacity.

There are numerous life-history types of juvenile salmon that reside in estuarine habitats for considerable time (e.g, "ocean-type" chinook stocks). Among these life-history types, survival to the adult stage is often correlated with estuarine residence and performance. Accordingly, our analyses emphasized subyearling, ocean-type chinook salmon (*Oncorhynchus tshawytscha*) because it makes maximum use of estuarine habitats and likely would be most sensitive to changes affecting the estuary. However, results of these analyses should also apply to other salmon species, particularly those with "ocean-type" life histories, such as chum salmon and some coho salmon.

3. Change in Hydrological Conditions

The magnitude and timing of river flow, which significantly influence estuarine habitat of juvenile salmon, have been highly modified at the watershed level. The predevelopment flow cycle of the Columbia River has been totally reshaped by hydropower regulation and irrigation withdrawal. While there is a prominent climate signal in river-flow variability over the period of the analysis (1859-present), the magnitude of maximum spring freshet flow has decreased over 40% from the predevelopment period (1859-1899) to the present. About 75% of this loss is due to flow regulation, about 20% to irrigation withdrawal, and about 5% to climate change.

The timing of maximum spring freshet flow has also changed, primarily because of hydropower and irrigation development of the river, resulting in an approximate 2-week shift earlier in the year (mean predevelopment date of 12 June compared to modern mean date of 29 May). Flow regulation now exacerbates early maximum spring freshet peak flows, such as the 23 April freshet peak in the year 2000. Gradual climate warming has also contributed to the change in freshet timing. Also, the annual average flow at the mouth has been reduced from about 8,500 m^3s^{-1} to less than 7,000 m^3s^{-1}, with about half of the decrease due to climate change and half to water withdrawal.

Changes in hydrology have had a significant impact on salmon habitat. Suppression of winter and spring freshet flows, compounded by flood-control diking and wetland reclamation below Bonneville Dam, have eliminated interactions between the lower river and its floodplain. Substantial over-bank flows are now rare (for example, four times in the last 50 years above 24,000 m^3s^{-1}) as compared with a predevelopment

flooding frequency of about every 2 years at flows above 18,000 m^3s^{-1}. While isolation of the river from its floodplain has enabled community development and commerce, it has also blocked access to salmon rearing habitat in riparian areas and backwater channels during flood events. Input of large woody debris that would have been produced and transported during such events in the upper tidal floodplain also has been virtually eliminated.

Riverine sediment transport to the estuary, which is an important process affecting the quantity and quality of estuarine habitat for salmon, is highly correlated with peak river flows. Although it is impossible to precisely separate the effects of flow regulation and irrigation withdrawal from climate variability, it is estimated that the corresponding change in annual average sediment transport (at Vancouver, Washington) for 1945-1999 flows has been about 50-60% of the virgin 19th-century (1858-1899) sediment transport; reduction in sands and gravels is higher (>70% of predevelopment) than for silts and clays.

In addition to peak spring freshet flow and sediment transport changes, the frequency in river flow cycles is highly altered by the hydroelectric system's peaking cycle. Low frequency variations with periods between approximately two years and six months have been suppressed, and high-frequency variations with periods of a week or less have been accentuated.

Finally, freshet styles have been strongly influenced by human actions and climate. Of the three types of spring freshet, two involve the melting of a large winter snow pack, with or without heavy spring rains. Because accumulation of the snowpack begins six months before the freshet, high flows related to melting of the winter snowpack can be controlled by drawdown of reservoirs before the freshet and storage during the freshet. Freshets related to an abnormally wet spring cannot be anticipated in advance, but the gradual warming of the region has made accumulation of a low-elevation spring snowpack less likely. Climate change scenarios suggest that the region will be warmer with wetter winters in coming decades. Under these climate scenarios, winter snow packs will likely be smaller, decreasing the spring freshet volume. Winter flows will likely increase, with an increase in the number of winter high-flow events related to melting of the interior sub-basin snow pack.

4. Estuarine Habitat Opportunity

Changes in habitat availability (opportunity) in the estuary were assessed for juvenile subyearling chinook salmon using a two-dimensional numerical circulation model to simulate the occurrence and distribution of shallow-water, low-velocity habitat during predevelopment (1880) and modern (1997-1999) periods. Predevelopment and modern river flows and estuarine bathymetry were used to simulate and compare the habitat opportunity (total hours that "suitable habitat" occur in a one-month simulation period) for salmon in the historical and present estuary. "Suitable habitat" for juvenile salmon was operationally defined using two physical criteria: areas with water depths ranging from 0.1 to 2 m and areas with water velocities less than 0.3 m s^{-1}.

Results showed that the availability of suitable habitat varies significantly within the estuary in response primarily to bathymetry, but also to tides and river discharges. In particular, each of the following regions offer distinctive habitat conditions:

1)   lower-estuary peripheral bays (Youngs and Baker Bays),
2)   upper-estuary peripheral bays (Cathlamet and Grays Bays),
3)   the lower-estuary mainstem, and
4)   upriver tidal-freshwater mainstem.

Seasonal and inter-annual variability is also very significant in regions of the estuary, particularly in the upriver tidal-freshwater mainstem and upper-estuary peripheral bays, where habitat opportunity is reduced during freshet months. Based on meeting the velocity criterion in model simulations, habitat opportunity under modern river flows and estuarine bathymetry has generally declined in both the upriver tidal-freshwater mainstem and the upper-estuary peripheral bays (Cathlamet and Grays Bays), while it has not changed dramatically in the lower regions of the estuary.

Model simulations of habitat opportunity based on the depth criterion, however, provide very different results. Simulated depth regimes across the estuary suggest that habitat opportunity under modern flows and bathymetry has increased relative to historical conditions, except in the upper tidal-freshwater mainstem region. Yet important limitations in the representation of modern bathymetry in the hydrodynamic model limit confidence in the model simulation results based on the depth criterion.

Moreover, estimates based on the velocity criterion appear much less sensitive to model uncertainties than those based on the depth criterion. Since there is not equal confidence in the simulation results for each individual criterion, the modern and historical habitat opportunity, based on the depth and velocity criteria combined, cannot now be interpreted. Furthermore, because peripheral wetlands that were historically diked and filled are not well represented in the predevelopment bathymetry, the simulations may underestimate predevelopment habitat opportunity to an unknown degree.

Overall, model simulations have revealed several important features relating river flow and bathymetry to habitat opportunity:

First, the results suggest that habitat opportunity in some regions of the predevelopment estuary was more resilient to increasing river flows than it is in the modern estuary. Resilience in this context refers to a reduced rate of change (slope) when correlating hours of habitat opportunity with river flow. This result was evident only in the upriver tidal-freshwater mainstem region (above the main body of the lower estuary) and the upper-estuary peripheral bays (Cathlamet and Grays Bays).

Second, in the model simulations, estuarine bathymetry largely determined habitat availability as defined by both the velocity and depth criteria described above. In addition, simulations of habitat opportunity under predevelopment bathymetry but with modern flows again suggested that bathymetric changes and habitat loss may be more influential in changing habitat opportunity than flow regulation.

Third, seasonal changes in habitat opportunity have shifted between historical and modern conditions. Minimum habitat opportunity in the estuary is associated with freshets that now occur earlier in the year than they did in the late 1800s. The impact of advancing the period of minimum habitat opportunity for juvenile salmon is unknown.

These characterizations of change in shallow-water habitat are preliminary and must be viewed cautiously for the following reasons:

1) The methodology is novel, and its conceptual validation took priority over minimizing the effects of particular model assumptions and uncertainties on the results.

2) Although calibrated using an extensive array of physical oceanographic measurements in the estuary, the model predictions have not been empirically validated in regions without instrumentation, including the important shallow-water environments of Cathlamet Bay.

3) Inadequacies in the modern bathymetric data affect habitat opportunity estimates based on simulated velocities and (especially) depths.

4) Substantial shoreline wetland and floodplain habitat lost to diking and filling are not fully incorporated in the simulations.

5) Estimates of habitat opportunity are overly simplified because they consider only the absolute area of suitable habitat that meets the criteria, rather than the spatial (landscape) arrangement and connectivity of suitable habitat. Nevertheless, the results indicate that for each bathymetric scenario, river flow strongly affects habitat opportunity in critical subregions of the estuary.

5. Estuarine Habitat Capacity

The productive capacity of the estuary has likely declined over the last century through the combined effects of diking and filling of shallow-water habitats, shifts from a macrodetritus-based to a microdetritus-based food web, and effects of introduced species. Loss of approximately 65% of the tidal marshes and swamps that existed in the estuary prior to 1870, combined with the loss of 12% of deep-water area, has contributed to a 12 to 20% reduction in the estuary's tidal prism.

The absolute change in habitat area does not necessarily capture changes in habitat quality. For instance, while the dramatic loss of emergent and forested wetlands in the estuary has likely impacted foraging resources, the area of shallows and flats actually increased 7% between 1870 and 1980, which would have provided some additional foraging habitat. Due to the lack of historical data on the flora and fauna of these habitats, we have no means to objectively quantify the ecological effects of this habitat tradeoff.

Although a substantial decline in wetland primary production and associated macrodetritus for the estuarine food web is implied by direct loss of emergent, forested, and other wetland rearing areas, reduced macrodetrital input to the food web to some degree may have been supplanted by an increase in microdetritus from upriver sources. The increase is principally in the form of phytoplankton production from the hydropower and flood control reservoirs.

The modern food web, however, does not support the same diversity of salmon life-history types that occurred historically. The present microdetritus-based food web, which is centralized in the highly productive estuarine turbidity maximum region of the estuary, largely supports a pelagic food web that may only indirectly contribute to larger, yearling salmon.

Significant changes in the modern estuarine community through species introductions have not been assessed. However, the Asian bivalve, *Corbicula fluminea*, has expanded far into the lower mainstem reservoirs and tributary basins since its introduction into the estuary in 1938. *Pseudodiaptomus inopinus,* a calanoid copepod also introduced from Asia, has appeared prominently in the estuary since 1980, and American shad has grown to a substantial population in the Columbia River since its introductions to the Sacramento River in 1876-1877 and to the Columbia in 1885-1886.

Fifteen other non-indigenous fishes are now common in the estuary. The specific impacts on the estuarine ecosystem, and on juvenile salmon in particular, from any of these populations are speculative. However, given the tremendous abundance of *C. fluminea* and American shad (peak Bonneville Dam passage counts of 3×10^6), it is not unreasonable to expect that their consumption rates may have significantly modified the estuarine food web.

Predation on juvenile salmon in the estuary by piscivorous fishes, marine mammals, and birds has always been a mortality factor. Yet there are no data to compare historical and modern predation rates or predator populations. Several unique predator populations, including Caspian terns, have increased significantly in recent decades and could constitute potential limiting factors on juvenile salmon survival. A major limitation of contemporary predation studies is that predator consumption may be substantially affected by changes in salmon migration behavior associated with hatchery rearing and release programs.

6. Change in Juvenile Salmon Life History, Growth, and Estuarine Residence

Results of historical and contemporary fish surveys were compared to assess change in the potential of juvenile salmon to use estuarine habitats based on 1) life-history diversity of subyearling, ocean-type chinook salmon; 2) periods of estuarine residence; and (3) growth and size characteristics.

Our analyses indicate that the population structure and life-history diversity of subyearling chinook salmon have been simplified significantly since the early 1900s. Reflecting the variability in emergence timing, migration distances, and growth rates among populations throughout the watershed, juvenile chinook historically migrated to the estuary during much of the year, where they resided for various time periods before migrating to the ocean.

In the predevelopment period, subyearling chinook entered the estuary as fry in May and again as fry and fingerlings between July and August. Based on scale analyses, fish that resided in the estuary between June and July demonstrated rapid and substantial increases in mean length. To account for this average growth, many subyearling salmon would have resided in the estuary for as long as several months.

In contrast, contemporary patterns of estuarine use suggest that life-history diversity of chinook salmon has declined. Most data from modern fish collection are from marked, hatchery-reared fish, sampled predominantly along mainstem channels. Thus, the catches for these collections are correlated with the timing of hatchery releases, so that abundance patterns of juvenile chinook in the estuary now reflect management practices more than historical migration behaviors.

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Relative to historical descriptions of chinook salmon fry and fingerlings, modern fish enter the estuary considerably later (by at least 2 weeks), in pulses that coincide with hatchery releases, in a smaller range of fish sizes, and with a more homogeneous size distribution. Smaller subyearlings historically present during early fall are lacking in modern fish collections. Salmon size distributions suggest that the historical flux of subyearling chinook was continuous from spring through fall, with some evidence of estuarine residence throughout this period. Fish of a wide range of size classes resided in the estuary, including subyearlings that did not enter until late fall and may have overwintered in its lower reaches.

Yet today's hatchery-dominated group of chinook salmon is composed of relatively few fry and many larger subyearlings that may not remain in the estuary for extended periods. In contrast to the historical continuum of rearing behaviors for juvenile chinook salmon, three principal life-history types are now dominant in the basin: subyearling migrants that rear in natal streams and/or main rivers and a group of yearling migrants. Thus, the analyses suggest that ocean-type chinook salmon with estuarine-rearing life histories are now substantially reduced in importance relative to their historical levels.

Our interpretations of both historical and contemporary estuarine life histories and habitat use by juvenile salmon are limited by lack of systematic surveys in the estuary. And because many changes in the basin had already occurred by the time the 1916 survey was completed, the historical diversity of estuarine rearing behaviors may have been underestimated. Present-day diversity may also be underestimated by using data from monitoring programs that emphasized the migration and survival of hatchery yearlings and large subyearlings, but did not sample juvenile salmonids in many shallow-water habitats.

Recent surveys provide no data on rates of estuarine growth by juvenile salmon and relatively few estimates of estuarine residence times. Furthermore, modern residency estimates are rough approximations, since they are inferred from recapture times for groups of marked juveniles moving past an upper and a lower estuary sampling site rather than from measurements made directly on individual fish. The lack of scale or otolith samples from modern estuarine collections further limits interpretation of contemporary salmon life histories, growth, and residence times.

Despite many data deficiencies, the uniform sizes and rapid migrations of present-day salmon compared with those found at a nearby site sampled in 1916 are consistent with loss in diversity and the types of life-history responses we might expect from changes in the Columbia Basin during the last 80 years: extinction of some salmon runs; loss of both river reaches and shallow, estuarine habitats; flow modifications that have dampened established disturbance regimes and altered estuarine habitat; intensive harvest and other selection pressures; and hatchery programs that release large batches of similarly-sized juveniles over a short period.

Conclusions and Recommendations

The principal object of this analysis was to assess the potential impact of flow regulation on juvenile salmon utilization of the estuary. The analyses identified flow regulation and climate effects on hydrology and sediment transport, both of which have likely consequences for the estuarine physical environment. However, with the extant

data, it was not possible to separate these effects from compounding factors or to rank them in terms of effects on juvenile salmon.

Nevertheless, the analyses indicated that habitat and food-web changes within the estuary and other factors affecting salmon population structure and life histories have altered the capacity of the estuary to support juvenile salmon. Diking and filling activities in the estuary have likely reduced the rearing capacity for fry and subyearling life histories by decreasing the tidal prism and eliminating emergent and forested wetlands and floodplain habitats adjacent to shore. These habitats, which provide slow-water, off-channel areas during peak flows, refuge from predators, and sources of macrodetrital production, probably serve different rearing functions from the other kinds of shallow habitats that model simulations suggest may have increased within the peripheral bays and other areas of the estuary.

Despite these physical and ecological changes, simplification of the population structure and life-history diversity of salmon may be the most important factor affecting juvenile salmon performance. In the absence of data on present-day estuarine use by wild, subyearling ocean-type salmon, we concluded that patterns of salmon abundance, diversity, and residency in the modern estuary have been markedly influenced by basin-wide upriver habitat losses, overharvest, and production-oriented hatchery management practices.

Restoration of estuarine habitats, particularly diked emergent and forested wetlands, and flow manipulations to restore historical flow patterns might significantly enhance the productive capacity of the estuary for salmon. However, it is possible that historical changes in population structure and salmon life histories now prevent salmon from fully utilizing the productive capacity of estuarine habitats even in their presently altered state. Accordingly, efforts to improve or restore the estuary for salmon must be developed in concert with hatchery, harvest, and upriver habitat improvements to recover those life-history types that can benefit from estuary restoration.

In addition, a sound historical and evolutionary context for interpreting modern estuarine habitat conditions and for developing salmon recovery strategies is needed. In the absence of such a context, recovery actions may inappropriately target those few salmon life-history types and habitats that are abundant today, further reinforcing the symptoms of salmon decline rather than expanding the productive capacity of the basin. Continued emphasis on improving survival of a few dominant types of chinook salmon, particularly large hatchery yearlings and subyearlings with short estuarine residence times, may further narrow the distributions of size, migration timing, and rates of migration. This would result in concentrated use of the estuary and would thus prevent salmon from utilizing its full productive potential.

Recovery efforts should expand diversity of both salmon life-history and habitat opportunities to allow for the widest possible range of successful rearing behaviors. Efforts to significantly improve the productive capacity of the estuary for salmon should therefore encompass many habitats and life histories that are now rare or non-existent rather than those few that have come to dominate as a consequence of industrial development of the basin and intensive selection pressures from harvest and hatchery influences.

While the risk of extinction of many Columbia River populations implies the need for immediate recovery action, lack of data on estuarine habitat use by salmon

argues that further study may be necessary before we can define appropriate restorative measures. Both of these concerns can be addressed by initiating targeted restoration activities, where there is reasonable confidence in their ecological benefits, and by simultaneously collecting new data to better understand salmon habitat requirements and restoration needs. To achieve these ends, the following specific recommendations are offered:

1.   *Adopt an explicit ecologically-based conceptual framework for estuary management and restoration.*

A fundamental impediment to recovery efforts in the Columbia River Basin is the lack of an explicit ecological framework for salmon conservation. Such a framework is particularly important to direct recovery efforts in the estuary, where physical and biological interactions are complex and continually changing in response to tidal forces, river flows, and seasonal fluctuations in the composition of species assemblages.

Lack of information about the estuarine-rearing requirements of juvenile salmon results from a longstanding "production" approach to salmon management and research. This approach assumes the estuary is a simple migration corridor where mortality factors must be controlled, rather than a productive nursery ground where the varied habitat needs of diverse populations and life-history types must be protected.

In addition, the ecological requirements of salmon within the estuary must be placed in the broader context of factors at other life stages that shape population structure and life history, and thereby determine whether juvenile salmon can realize the full productive potential of the estuary.

2.   *Protect and restore opportunity for salmon to access emergent and forested wetlands in the estuary and riparian wetlands in the tidal floodplain*

Historical losses of peripheral floodplain, wetland, and riparian habitats from diking and filling activities in the Columbia River estuary have reduced available rearing habitat for salmon with subyearling life histories. Such effects may not be limiting to yearling, stream-type juveniles at present because hatcheries, harvest, and upriver habitat losses tend to favor these life histories. However, any effort to increase life-history diversity will require re-establishment of important rearing habitats that have been substantially modified or removed from the estuary.

Although fish use of tidal wetlands and floodplain habitats has rarely been investigated in the Columbia River, studies in other Northwest estuaries indicate that wetland restoration could offer a cost-effective method to improve salmonid rearing conditions. Re-establishment of more natural flow regimes in the basin might also diversify estuarine habitat opportunity and its associated variety of salmon rearing and migration behaviors.

3.   *Expand phenotypic diversity of salmon, including a broader range of sizes, times, entry, and residency in the estuary*

Although increased genetic and life-history diversity of salmon may ultimately require long-term expansion of habitat opportunity upriver and in the estuary, rapid progress in the use of existing or restored habitats could be made by expanding phenotypic diversity of salmon now heavily influenced by hatchery programs. Such

improvements could require reductions in hatchery releases or changes in hatchery rearing practices.

However, any management changes to benefit salmonid use of the estuary will require an improved accounting system and a greater degree of coordination of basin-wide hatchery programs than presently exists. For example, incomplete records of hatchery release groups, variations in rearing and release practices that confound interpretation of management effects, and difficulties in distinguishing the hatchery or wild origin of unmarked salmon preclude a full accounting of the influence of hatchery practices on salmon behavior and performance in the estuary.

4. *Monitor variations in life-history diversity, habitat use, and performance of juvenile salmon in the estuary*

Because the abundance and life histories of salmon in the estuary are linked to source populations and habitats upstream, changes in life-history diversity and the relative proportions of wild juveniles in the estuary may indicate whether recovery efforts throughout the basin are having a positive effect. Unfortunately, there is no established monitoring program to describe long-term trends in salmon rearing behaviors in the estuary. Neither have salmon scales or otoliths been collected or archived to evaluate changes in estuarine life-history patterns since 1914-1916.

Most contemporary estuarine studies are of short duration, including numerous local impact studies, and only rarely have they sampled many of the shallow habitats typically preferred by smaller subyearling salmon. Furthermore, the most consistent monitoring in the estuary has emphasized the migration rates and survival of large, hatchery-tagged fish, and poorly represents wild, ocean-type species and life histories that are likely most dependent upon estuarine conditions. A more representative sampling program is needed to monitor variability in the estuarine life histories and performance of salmon.

5. *Review the scientific basis for proposed habitat and bathymetric changes in the estuary relative to the restoration goals of the Columbia Basin Fish and Wildlife Program*

Habitat changes and economic activities within the estuary have been evaluated independently of management or restoration efforts that affect salmon and their habitats elsewhere in the Columbia River Basin. For example, the potential effects of ongoing or proposed estuarine dredging, spoil disposal, or habitat restoration activities on the Columbia Basin Fish and Wildlife Program have not been explicitly evaluated.

Because all anadromous salmonids in the Columbia River pass through or rear in the estuary before migrating to the ocean, changes in estuarine conditions could determine the effectiveness of salmonid recovery efforts throughout the basin. Modeling results show that estuarine habitat opportunity for salmonids is sensitive to bathymetric change. In addition, the response of predacious birds to dredge-spoil islands artificially created and maintained in the lower estuary illustrates that at least some estuarine habitat changes may have unexpected ecological consequences.

Despite these risks, impact assessments associated with dredging and disposal activities have usually focused on localized impacts and have not considered salmonid responses to changes in habitat opportunity or capacity at a landscape scale. Nor have

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they considered the history of incremental change upon which each new project is superimposed or the broader responses of the ecosystem to physical habitat modifications.

6. *Use physical observations and hydrodynamic modeling to assess the effects of bathymetric change, flow regulation, and alternative restoration designs on habitat opportunity for juvenile salmon*

Our modeling methodology has proven to be a useful approach for evaluating the relative effects of flow modification and bathymetric change on habitat opportunity for salmon. However, its present application is limited by several critical data gaps, including the lack of present-day, high-resolution bathymetric data and physical observations for shallow regions of the estuary. For example, the ability of the model to characterize physical habitat opportunity relative to the depth criterion (much more so than opportunity determined with respect to the velocity criterion) was very sensitive to assumed bathymetric configurations in the shallow areas of the estuary. This emphasizes the need to obtain accurate bank-to-bank bathymetric data for the lower river and estuary if there is to be an improved understanding of the impacts of river flow on physical habitat opportunity.

7. *Review results of estuarine predation studies in the context of salmon population and habitat change*

It is unclear whether the high rates of salmon predation by Caspian terns and other marine birds in the estuary is a significant factor affecting salmon recovery or an ecological symptom of other changes, including alteration of estuarine habitats, simplification of the geographic structure of salmon populations, and reduced variation in salmon rearing and migration behaviors.

For example, high predation rates on juvenile salmonids could result from replacing a broad continuum of salmon life-history types with punctuated releases of large hatchery fish that are concentrated in relatively few estuarine habitats over reduced periods of time. Hatchery-induced changes in surface-feeding behavior could also be a factor increasing the vulnerability of salmon smolts to predators. Emphasis on estimating predation rates alone may thus lead to inappropriate salmon recovery proposals unless these results are evaluated in a broader historical and ecological framework.

8. *Assess the effects of altered habitats and food webs on the capacity of the estuary to support juvenile salmon*

Results of this review indicate that a variety of ecological changes may have affected the capacity of the estuary to support wild subyearling chinook salmon. These changes include loss of floodplain and other wetland habitats, the effects of climatic changes on physical processes and estuarine food webs, interactions with an increasing number of nonindigenous species, and shifts in the timing of established patterns of river flow and salmon migrations. Unfortunately, the direction or magnitude of these ecological changes cannot be assessed from the limited empirical data available.

For example, the effects of altering food-web sources through habitat modifications have not been directly evaluated. We also have little data to assess the effects of a two-week advance in the spring freshet due to flow regulation and a substantial delay in peak salmon migrations due to hatchery and other influences. If

estuarine prey production cycles and salmon migration behaviors are adaptive, and linked to flow variations, then such changes could create a mismatch between salmon and their prey resources, reducing the productive capacity of the estuary.

Changes in the coarse and fine sediment budgets, particularly the quality of organic matter input to the system, are also poorly understood.

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INTRODUCTION

In the late 18th century, the entrance to the "Great River of the West," was expected to provide a Northwest Passage across the American continent and an inland highway for transpacific trade. However, the long-awaited Northwest Passage repeatedly eluded European maritime explorers. Based on the currents and discolored water encountered near shore, Spanish explorer Bruno de Heceta believed he had found the continental passageway in 1775, but did not attempt to enter the river he called the Rio San Roque. He was soon followed by an armada of unsuccessful Britons. James Cook tried three times to find the river, including a final attempt in 1778, when he sailed past the Columbia River mouth sometime during the night.

A decade later, John Meares could not see beyond the long wall of surf and concluded that no river existed. He proclaimed his displeasure by dubbing the inlet Deception Bay and the rocky cape at its northern end Cape Disappointment (its present name). On 27 April 1792, George Vancouver mistakenly discounted signs of discolored water as just "some streams falling into the bay," and continued sailing northward past the river entrance. Finally, a few weeks later, American Robert Gray sailed the *Columbia Rediva* across the bar at Cape Disappointment and into the mouth of the Great River (Egan 1990, Dietrich 1995).

Difficult as the river was to find, its strategic importance was never in doubt. Gray quickly verified the Columbia's commercial potential; his first official acts included trade with the Chinook natives--a nail for two salmon, two nails for a beaver skin, a sheet of copper for four otter pelts. Thus, Gray not only redrew the regional map, but in symbolic exchanges of two of the river's principal assets--furs and salmon--he ushered in new and far-reaching economies that would forever reshape the Columbia River ecosystem. Along the short 15 miles he ventured upstream, Gray collected more than 3,000 otter pelts, which he subsequently sold in China (Egan 1990, Detrich 1995).

While the commercial importance of the Columbia River estuary was obvious from the beginning, the natural economy of its murky waters remains as elusive today as its entry was to early explorers. The vast river network of the Columbia Basin drains an area about the size of Texas and funnels through a narrow tidal reach at the mouth in a roiling slurry of fresh and salt water, sediments, and organisms. From this narrow constriction of a few miles across its mouth, the Columbia River shoots a powerful jet of river water into the North Pacific, a plume whose signature can be traced as far south as San Francisco.

If the entrance to the mighty river itself was difficult to discover, how much more so will be the intricate physical and biotic interactions at its ocean juncture? It is not surprising that interest in the estuary these last 200 years has centered on its practical uses and resources rather than on the obscure ecological interrelationships that support them. Yet crises have a way of exposing hidden obstructions and redirecting the imagination. The rapid decline of Pacific salmon has exposed the need to more fully explore the ecological depths of the Great River's estuary. This report is part of that exploration.

In the last several decades, the Columbia Basin's historically bountiful populations of Pacific salmon have diminished to a small fraction of their former diversity and abundance. Numerous populations have declined or become extinct as a consequence of industrialized fisheries, habitat loss, hydropower development, and salmon hatchery programs. Since 1991, a dozen Columbia River salmon stocks have been added to the list of threatened and endangered species under the U.S. Endangered Species Act (ESA). While traditional environmental assessments have often focused on obvious habitat changes upriver, including the loss of spawning and rearing area following construction of large hydroelectric dams, questions are now being raised about the estuary's role in salmon decline and potential recovery.

One recent analysis, for example, proposes that small survival improvements when spring and summer chinook salmon enter the estuary and ocean could yield some of the most significant population increases (Kareiva et al. 2000). The need to better understand the effects of the Columbia River estuary and plume on salmon populations was recognized in recent policy changes governing salmon recovery programs throughout the basin.

On 12 September 1996, Congress amended the Pacific Northwest Electric Power Planning and Conservation Act of 1980 to include a new section that requires the Northwest Power Planning Council (NPPC) to "consider the impact of ocean conditions on fish and wildlife populations" when recommending hydropower mitigation projects for the Columbia River Basin.

This new amendment to the Power Act applies directly to anadromous fish populations, particularly Pacific salmon and steelhead, which have continued their precipitous decline despite decades of effort to mitigate effects of harvest and hydroelectric development in the basin. This legislation also focused new attention on the estuary, which provides important rearing habitat for juvenile salmon during their seaward migration and is directly impacted both by ocean conditions at the mouth and the effects of upstream hydropower development.

Concerns about the estuary and ocean represent a significant departure from previous management policy in the Columbia River Basin. Until now, restoration has focused almost exclusively on the freshwater phase of the salmon life cycle, even though salmon spend most of their lives at sea. Recent research has shown that decades-long shifts in climatic and oceanic conditions can produce fluctuations in salmon production across the entire North Pacific Ocean (Francis and Sibley 1991, Beamish and Bouillon 1993, Mantua et al. 1997). Such natural variability must be taken into account to develop appropriate recovery goals, actions, and expectations for Columbia River salmon.

Legislation that requires resource managers to look beyond fresh water thus recognizes that marine, estuarine, and riverine environments are each components of an extended salmonid ecosystem and cannot be treated independently (ISG 2000, Bisbal and McConnaha 1998). While clearly it is not possible to control fluctuations in the North Pacific Ocean, hydroelectric development and other upriver alterations directly affect the estuarine and nearshore coastal habitats of salmon as well as the health and diversity of salmonids that enter the ocean. Ultimately, these factors may decide whether salmon from the Columbia Basin can realize the

full productive potential of the ocean under any particular set of environmental conditions.

In response to the legislative mandate to consider the ocean, the NPPC thus recommended two management strategies:

1) improve estuarine and nearshore habitat conditions, which have been adversely affected by local habitat changes and upriver management activities; and

2) preserve the diversity of life-history characteristics in salmon, which allows populations to withstand environmental fluctuations (NPPC 1997).

The NPPC further recommended several research initiatives to improve understanding of ocean effects on fish and wildlife management activities, including "a synthesis of what is known about the impacts of the construction and operation of the Columbia River hydroelectric system on the hydrology, habitats, and ecology of the Columbia River estuary and river plume and opportunities for management actions related to this understanding (NPPC 1998)."

In 1999, the National Marine Fisheries Service formed an estuarine research team to evaluate whether existing information is adequate to (1) interpret effects of the hydroelectric system on the Columbia River estuary as outlined in the NPPC research initiative; and (2) more broadly support NPPC strategies concerning ocean viability, for example, improvement of estuarine and nearshore habitats and preservation of life-history diversity in salmon.

This review summarizes our assessment of conditions in the Columbia River estuary. Our purpose is to offer management recommendations for improving estuarine conditions for salmon, or alternatively, to identify research that will be needed before appropriate management changes can be adequately defined. We began by asking four key questions about salmon in the Columbia River estuary:

1) What habitats and processes support native salmon populations during the estuarine phase of their life cycle?

2) Have changes to the estuary had a significant role in salmon decline?

3) What have been the impacts of flow regulation on the hydrology, habitat, and biological interactions in the estuarine ecosystem?

4) What estuarine conditions are necessary to maintain diversity of salmonids in the Columbia River Basin?

To address these questions, we identified these five research objectives, which are the subject of this review:

1) Develop a conceptual model that identifies the linkages between estuarine forcing elements and the structure and resilience of salmon populations.

2) Assess historical changes in climate, external forcing, and estuarine physical processes relevant to salmon life histories.

3) Assess feasibility of modeling estuarine response to historical and future changes in climate and hydropower operations through a preliminary modeling exercise.

4) Assess feasibility of reconstructing salmon life-history patterns in the Columbia River estuary prior to hydropower development, and contrast these patterns to those of the present.

5) Assess potential for hydropower management to re-establish conditions favorable for diverse salmonid populations and life histories and define other modifications and recovery actions needed to achieve these ends.

In this review, we first analyze published and unpublished data and summarize the results of model simulations. We then describe key estuarine linkages to salmon and assess changes in the estuary's capacity to support salmon. Based on available knowledge of estuarine ecology and juvenile salmon estuarine residence, we focused our analyses on subyearling fish, primarily juvenile fall chinook salmon.

Because there are few historic data on juvenile salmon in the Columbia River estuary, we use simulation modeling to characterize the historic and present opportunity for subyearling salmon to access shallow-water habitat. For this purpose, we define opportunity as the total number of hours that shallow-water habitats are potentially available to salmon under selected tidal, river-flow, and bathymetric conditions. We also examined historical changes in the capacity of estuarine habitat to support subyearling salmon due to physical or biological factors.

Our assessment considers the effects of natural and anthropogenic change in the estuary, as well as historic impacts on salmon populations themselves, which may affect the ability of these fish to fully use the estuarine habitats available to them. Our analyses were designed to distinguish the effects of flow regulation from bathymetric and other changes to the estuary and to put these recent anthropogenic influences in the context of long-term climatic fluctuations.

The first two chapters establish the context for our evaluations and include a history of changes in the basin that have affected salmon populations and estuarine conditions (Chapter 1) and the conceptual approach upon which our specific analyses and interpretations are based (Chapter 2).

The following four chapters describe results of these analyses:

• Hydrologic and climatic fluctuations in the Columbia River Basin for the last 140 years and the effects of hydroelectric operations and other management activities on established flow patterns (Chapter 3).

• A preliminary series of model simulations to compare availability of estuarine habitat for salmon under historic and present bathymetric and flow conditions (Chapter 4).

• The status of knowledge about ecological changes within the estuary that have affected habitat quality and rearing capacity for salmon (Chapter 5).

• The performance of salmon in the estuary using indicators of growth and life history (Chapter 6).

Finally, we summarize the results of these analyses and their implications and provide recommendations for future estuarine management and research.

Because so few data have been collected on juvenile salmon and their habitat use in the estuary, the depth of our estuarine exploration is necessarily limited. For example, although our habitat modeling demonstrated the sensitivity of the ecosystem to changes in flow and bathymetry, the results are preliminary because existing bathymetric data are inadequate to fully resolve habitat response to these changes.

However, this review is more than just a compilation of facts and conclusions about the estuary, since it proposes an alternative framework for evaluating the effects of estuarine habitat change on Columbia River salmon populations. We believe such a framework is a necessary prerequisite for understanding the role of the estuary in either salmon decline or recovery. Accordingly, this review is as much an illustration of how such a framework can be applied to studies in the Columbia River estuary as it is a presentation of results based on that framework.

1. ESTUARINE DEVELOPMENT HISTORY AND SALMON DECLINE

Estuary Description

With a watershed of roughly 660,500 km^2, encompassing seven states, two Canadian provinces, and two major continental mountain ranges (Cascades and Rockies), the Columbia River is the second largest river in the United States. The river and estuary are dominant features in the circulation of the Northeast Pacific Ocean as well, with a mean annual discharge at the mouth of ~5,500 m^{3}s^{-1}. We define the Columbia River estuary (Fig. 1.1) to include the free-flowing waters that are influenced by oceanic tides: a reach spanning 240 km from the river's ocean entrance to the base of Bonneville Dam. Relative to juvenile salmon migration along the estuarine gradient, this system includes three physiographic subsystems:

1) The tidal freshwater portion (or "fluvial region;" Simenstad et al. 1990b) from Bonneville Dam to the maximum upstream extent of salinity intrusion (~55 km from the entrance);

2) The brackish-oligohaline region above the open expanse of the main estuary (upstream from ~30 to 55 km from the entrance); and

3) The broad, euryhaline region in the lower 30 km of the estuary. Ecological studies in the estuary during the early 1980s further partitioned the euryhaline region into seven subareas: (1) entrance, (2) Trestle and Baker Bays, (3) Youngs Bay, (4) estuarine channels (5) mid-estuary shoals of the "estuarine mixing zone," (6) Grays Bay, and (7) Cathlamet Bay (Simenstad et al. 1990b).

This lower "estuarine" area encompasses a complex network of main, distributary and dendritic tidal channels, unvegetated shoals, emergent and forested wetlands, and extensive mudflats in peripheral bays. Approximately 26,550 ha (about 71.2%) of the 37,289 ha of this estuarine region is composed of shallow-water habitats (6 m or less relative to mean lower low water). Except in peripheral bays, where silt and clay sediments dominate, most of the estuary's sediments are composed of sand. More detailed descriptions of the river flow and sediment transported through the estuary appear in following chapters.

Estuarine Requirements of Juvenile Salmon

All anadromous salmonids (*Oncorhynchus* spp.) that survive to reproduce pass through estuaries at least twice during their life cycle: once as juveniles en route to the Pacific Ocean and again as adults when they return to spawn in their natal streams. In the estuary all outmigrating juveniles must make the transition from shallow, freshwater, lotic environments to a deep, salty, open ocean within a period of days to months. Estuaries are often presumed to offer three advantages to juvenile salmon for making this transition:
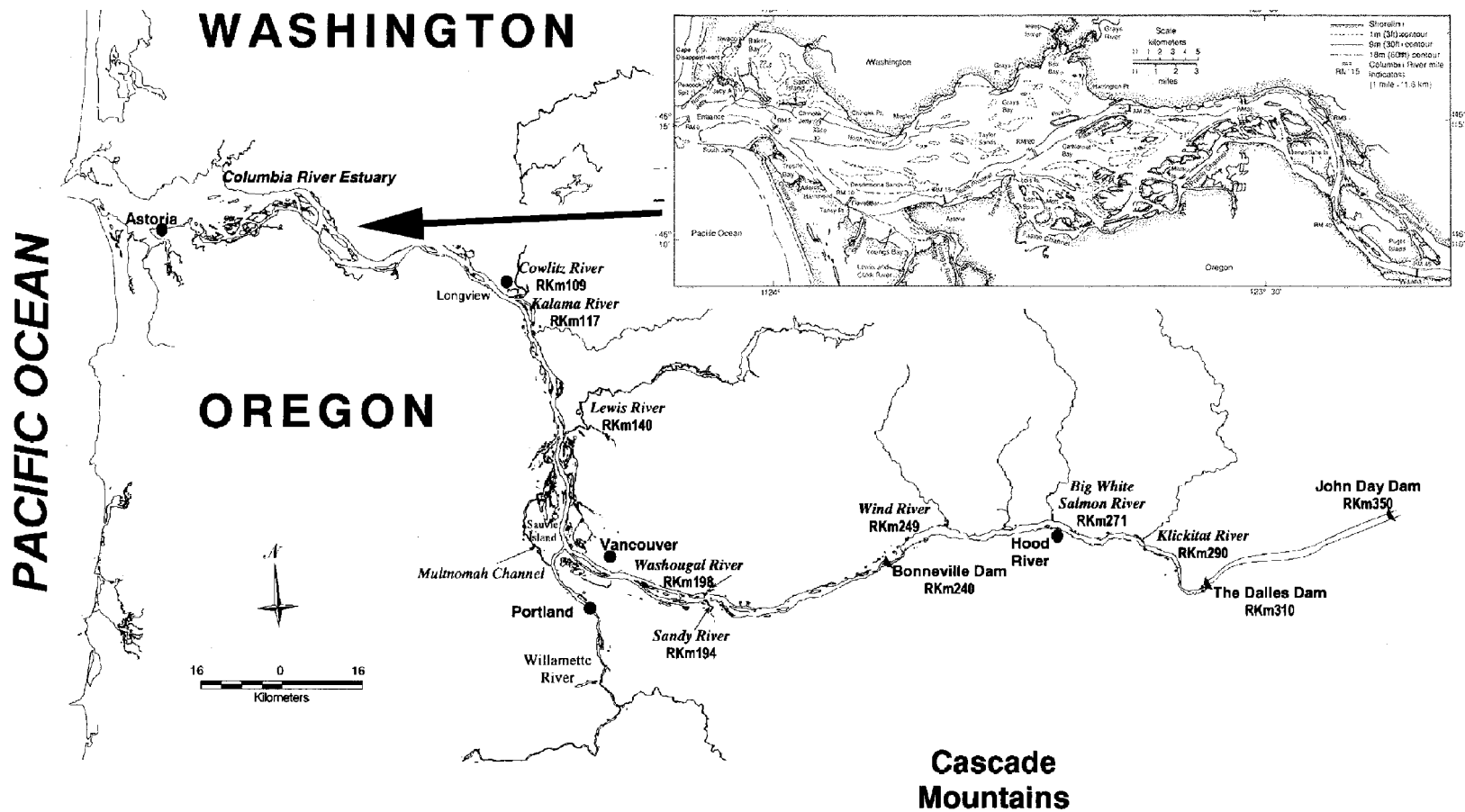
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Figure 1.1. Study area for this review extends from the Columbia River mouth to the upper extent of tidal influence at Bonneville Dam (RKm 240). Inset shows the estuarine study region (to RKm 75) for the Columbia River Estuary Data Development Program (Simenstad et al. 1990a).

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(1) a productive feeding area capable of sustaining increased growth rates, (2) a temporary refuge from marine predators, and (3) a physiological transition zone where juvenile fish can gradually acclimate to salt water (Simenstad et al. 1982, Thorpe 1994).

Pacific salmon species and populations have evolved diverse strategies for using all available freshwater and estuarine nursery habitats within a river basin (Healey 1982, Groot and Margolis 1991). The duration of estuarine residence varies considerably among species and sizes of juvenile salmon. Salmonids that rear in fresh water for a year or more before migrating downstream (some chinook (*O. tshawytscha*), sockeye (*O. nerka*), and coho (*O. kisutch*)) are believed to move rapidly through the estuary and may not spend substantial periods adapting to salt water before they enter the ocean. These are frequently referred to as "stream-type" fish.

On the other hand, subyearling migrants that enter the estuary as fry or fingerlings, so-called "ocean-type" salmon, exhibit a wide range of residence periods depending on the species. Pink salmon (*O. gorbuscha*), for example, exhibits little estuarine rearing, chum salmon stays in estuaries for days to weeks, and subyearling chinook salmon may remain for up to several months (Thorpe 1994).

Chinook salmon, which has the greatest diversity of juvenile life-histories among all Pacific salmon (Healey 1991, Wissmar and Simenstad 1998), has the most varied patterns of estuarine use. Healey (1982) proposed that chinook salmon is the most estuarine dependent of salmonid species since virtually all life-history types spend time feeding and growing in estuaries, and fry migrants may rely entirely on the estuary for nursery habitats. Chum salmon has been classified as the second most estuarine dependent species (Healey 1982, Simenstad et al. 1982).

Regardless of the residence times of individual fish, juvenile salmon may occur in the estuary all months of the year, as different species, size classes, and life-history types continually move downstream and enter tidal waters from multiple upstream sources. Peak estuarine migration periods vary among and within species, suggesting that different life-history strategies may provide a mechanism for partitioning limited estuarine habitats (e.g., Myers and Horton 1982). The varied juvenile life histories in chinook salmon are manifest in the wide range of sizes and times of estuarine entry (Rich 1920, Healey 1982). In the Columbia River estuary, subyearling chinook salmon is most abundant from May through September but is present all months of the year (Rich 1920, McCabe et al. 1986). Rich (1920) first reported that, for each chinook brood in the Columbia River, juvenile migrations span an 18-month period, including fry that migrate soon after emerging in December and yearlings that do not leave until late their second spring.

The size of chinook salmon at the time of ocean entry may reflect the various alternative rearing options available to juveniles before they make the complete transition to an ocean environment. Large numbers of chinook enter southern British Columbia estuaries as fry and leave at relatively small sizes (60 or 70 mm) at about the time subyearling chinook smolts migrate downstream (Healey 1982). In the Nanaimo River system on the east coast of

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Vancouver Island, subyearling smolts reside in the outer estuary in June and July and some remain year-round. The earlier disappearance of most chinook from southern British Columbia estuaries may reflect the availability of protected habitat along the complex archipelago of the Strait of Georgia (Healey 1982). Whereas fewer fry migrants have been reported in coastal Oregon estuaries (e.g., Reimers 1973, Myers 1980), many subyearling chinook use estuaries for longer periods, often through the summer and into early autumn, and migrate at relatively large sizes. Estuaries along the open Oregon coastline thus may be particularly important as shelter for juvenile salmon that must migrate directly into an open ocean environment.

Many studies indicate that the movements of juvenile salmon and their habitat use within estuaries are size-related. Small chinook and chum salmon (subyearling) fry usually occupy shallow, nearshore habitats, including salt marshes, tidal creeks, and intertidal flats (Levy and Northcote 1982 , Myers and Horton 1982, Simenstad et al. 1982, Levings et al. 1986). As subyearling salmon grow to fingerling and smolt stages, their distribution typically shifts toward deeper habitats farther away from the shoreline (Healey 1982, 1991, Myers and Horton 1982). Although the specific size transitions may vary, numerous estuarine studies have found juvenile salmon distributed along a habitat continuum: juvenile chinook and chum less than 50-60 mm fork length (FL) occur primarily in shallow water (e.g., <1 m); fish 60-100 mm FL are found in slightly deeper habitats (shoals, distributary channels); and fish greater than 100 mm FL may be found in both deep- and shallow-water habitats. This direct relationship between size and habitat depth tends to break down during hours of darkness, when schooling fry or fingerlings often disperse from shore (Schreiner 1977, Kjelson 1982, Bax 1983, Healey 1991, Salo 1991).

The distribution of juvenile salmon in the Columbia River estuary is consistent with this notion of differential habitat use based on fish size. McCabe et al. (1986) reported that subyearling chinook in shallow intertidal habitats of the Columbia River estuary were smaller than subyearlings captured in deeper pelagic areas. Similarly, large yearling migrants may spend relatively little time in shallow estuarine habitats. A 1980-1981 survey of the estuary, for example, found most yearling chinook salmon at deeper channel sites rather than at intertidal sites sampled near shore (Bottom et al. 1984).

Rapid changes in salinity gradients, water depths, and the accessibility of habitats impose important ecological and energetic constraints that salmon do not experience in fresh water: salmon must continually adjust their habitat distribution, particularly in shallow-water areas, with twice-daily tidal fluctuations and seasonal variations in river flow. The landscape distribution of habitats throughout an estuary thus may be important in juvenile salmon adaptation to tidal and seasonal changes. For example, in most estuaries, salmon fry move twice daily from low-tide refuge areas at the junction of major and minor channels to salt marsh habitats at high tide and back again (Healey 1982, Levy and Northcote 1982). Chum and chinook salmon fry remain in marshes of the Fraser River estuary for an average of 11 and 30 days, respectively (Levy and Northcote 1982). Thus, access to suitable low-tide refuge located immediately adjacent to marsh habitats may be an important factor in salmon production and survival as juveniles traverse the estuarine landscape.

Appropriate sequences of habitat distributed across the entire estuarine salinity gradient also may be necessary to support the seasonal migrations of juvenile salmon (Simenstad et al. in press). Throughout their migration and rearing period in estuaries, subyearling migrants traverse a continuum of salinities, depths, and water velocities as they gradually grow and migrate from upper tidewater to lower estuary and from shallow nearshore to deeper offshore areas. For species like chum and chinook salmon that remain in the estuary for extended periods, a broad spectrum of habitat types may be needed to satisfy feeding and refuge requirements within each salinity zone. But even large coho smolts may require a sequence of habitat types to allow for extended holding periods during their relatively brief stay in the estuary. Radio-tagged coho salmon in Grays Harbor estuary (Washington), for example, interspersed periods of passive downstream movement in strong currents with periods of holding in low-velocity habitats (Moser et al. 1991). Because the parr-smolt transformation is a key period when salmon gather the olfactory information they need for successful homing, and because the cues for imprinting may depend upon environmental gradients experienced during migrations and physiological changes, habitat sequences at a landscape scale may be important even for those salmonids that move through the estuary relatively quickly (Dittman et al. 1996).

Marsh habitats, tidal creeks, and associated dendritic channel networks may be particularly important to small subyearling salmonids as areas of high secondary production of insect and other invertebrate prey; sources and sinks for detritus; and potential refuge from predators afforded by complex habitat structure, including sinuous channels, overhanging vegetation, and undercut banks (e.g., Levy and Northcote 1982, McIvor and Odum 1988, Gray et al. in review). Salmonid production in Northwest estuaries is supported largely by detrital food chains through a variety of animals that live in or near the estuary bottom (Healey 1979, 1982). Habitats that produce or retain detritus are therefore particularly important. Detrital sources vary along the estuarine tidal gradient but include emergent vegetation in tidal wetlands, low intertidal and subtidal eelgrass, macro-algal beds, and epibenthic algae (Naiman and Sibert 1979, Sherwood et al. 1990). Historically, before the Columbia River was isolated from its floodplain, considerable organic matter was likely imported into the estuary during seasonal freshets and winter flooding events.

In the Columbia River estuary, low-velocity, peripheral bay habitats (e.g., Baker Bay, Youngs Bay, Grays Bay) and the estuarine turbidity maximum in the mid-estuary are regions where organic matter is concentrated and invertebrate prey production and fish and macro-invertebrate feeding are elevated relative to other estuarine locations (Bottom and Jones 1990, Jones et al. 1990, Simenstad et al. 1990). Loss of historic wetlands and macro-algal habitats (e.g., mud and sand flats) within the estuary and enhanced phytoplankton production in impoundments upriver may have shifted estuarine food chains from macrodetrital to microdetrital sources (Sherwood et al. 1990). Such changes would likely benefit food chains supporting pelagic-feeding fishes such as northern anchovy (*Engraulis mordax*), longfin smelt (*Spirinchus thaleichthys*), surf smelt (*Hypomesus pretiosus*), Pacific herring (*Clupea harengus pallasi*), and American shad (*Alosa sapidissima*) with commensurate loss of food webs supporting epibenthic-feeding fishes like juvenile salmon.

Historical Change in Salmon Populations and Estuarine Habitats

To understand patterns of habitat use within the estuary, we must account for changes at all life stages that shape the structure and life histories of salmon populations. Salmon species composition, abundances, sizes, and migration periods in the estuary are all linked to changes upriver or in the ocean that determine which populations and juvenile life-history types survive to enter tidewater. The biological characteristics and density of salmon in the estuary may be influenced by multiple factors, including selective harvest in ocean and river fisheries, adult access to upriver spawning and rearing habitats, rearing and release practices in hatcheries, and climate and river flow. Historic changes to Columbia River populations and habitats (see Appendix), which may affect salmon rearing conditions in the estuary, are detailed elsewhere (NRC 1996, Lichatowich 1999, ISG 2000) and briefly summarized below.

Population Decline

Prior to European settlement, the Columbia River system sustained annual adult returns from 11 to 16×10^6 salmon,[1] of which native Americans likely harvested between 4.6 and 6.3 x 10^6 fish (Craig and Hacker 1940, NPPC 1986). All five species of Pacific salmon were historically present in the Columbia River, although pink salmon abundance was always quite low (Heard 1991, NRC 1996). Of an area more than 422,000 km^2 originally available for salmon spawning and rearing, less than 190,000 km^2 (<45%) is now accessible (Fig. 1.2, NRC 1996). In the Snake River, ocean-type chinook salmon now occupy only ~17% of the historic habitat (Hassemer et al. 1997). Virtually none of the historic salmon habitat in the portion of the Columbia River that lies in Canada is now accessible. Through habitat loss and other changes, present natural production of salmon in the Columbia River Basin has been reduced to approximately 12% of historic levels. Since 1991, sustained population declines have resulted in listings of 12 salmonid stocks as Threatened or Endangered under the Endangered Species Act (Table 2.1).

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[1] Other estimates of total run sizes are often significantly lower, such as 7.5×10^6 (Chapman 1986) and 6.2×10^6 (PFMC 1979).
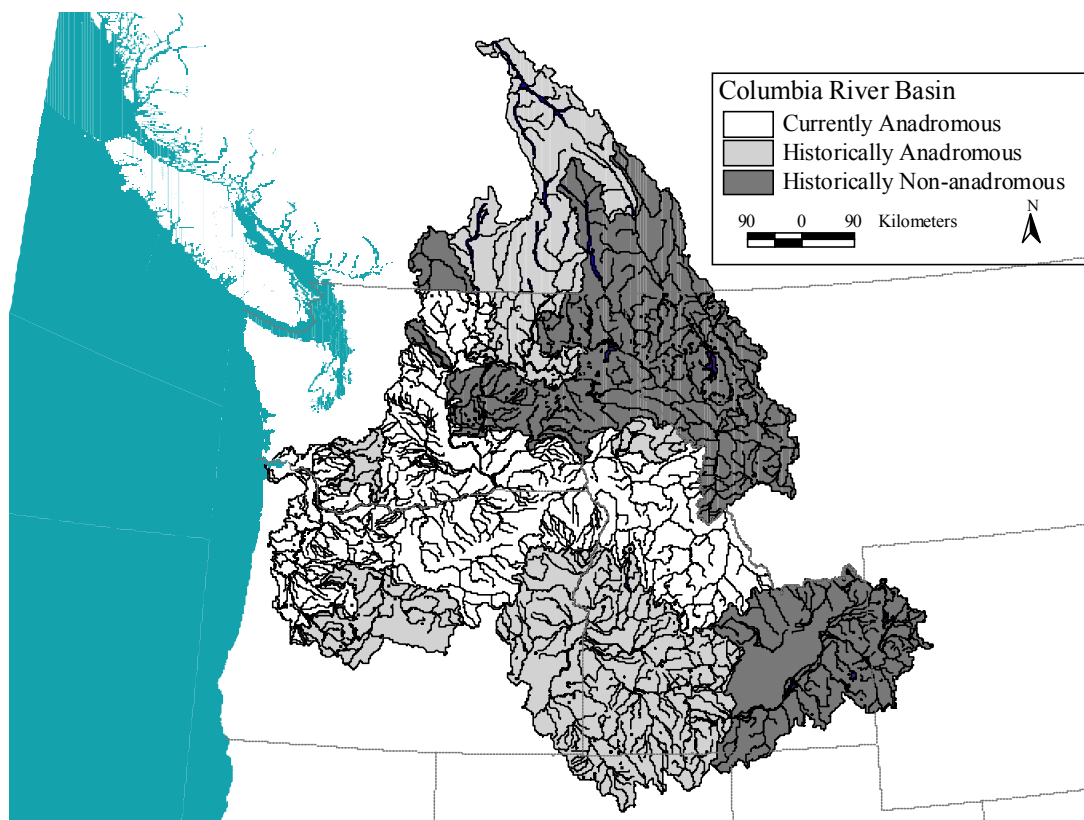
Figure 1.2. Historic and contemporary salmon distribution in the Columbia River watershed
(courtesy of Blake Feist and University of Washington School of Aquatic and
Fishery Sciences).

Table 1.1. Listings and proposed listings of Columbia River salmonids under the Endangered
Species Act (ESA). Listings include various Evolutionarily Significant Units (ESU)
within each species as designated by the National Marine Fisheries Service.

Species	ESA Status	ESU	Date
Coho Salmon	Candidate	Lower Columbia River/ Southwest Washington	Candidate: July 1995
Chinook Salmon	Listed	Snake River fall-run	Threatened: April 1992
		Snake River spring/summer-run	Threatened: April 1992
		Lower Columbia River	Threatened: March 1999
		Upper Willamette River	Threatened: March 1999
		Upper Columbia River spring-run	Endangered: March 1999
Chum Salmon	Listed	Columbia River	Threatened: March 1999
Sockeye Salmon	Listed	Snake River	Endangered: November 1991
Steelhead	Listed	Upper Columbia River ESU	Endangered: August 1997
		Snake River Basin	Threatened: August 1997
		Lower Columbia River	Threatened: March 1998
		Upper Willamette	Threatened: March 1999
		Middle Columbia River	Threatened: March 1999
Coastal Cutthroat	Proposed	Southwestern Washington/ Columbia River	Threatened: April 1999

Different species and life-history types of salmon occur in somewhat different spawning and rearing areas of the Columbia River Basin (Figs. 1.3 and 1.4). Thus, the geographic patterns of habitat and population loss on the landscape may determine the particular species and life-history types that are represented in the estuary. Chum salmon are confined principally to the lower Columbia River tributaries, excluding the Willamette River drainage; coho salmon once occupied all tributaries west of the Cascade Mountains and larger tributary systems (e.g., Yakima, Wenatchee, Entiat, Methow, Spokane, and Grand Ronde Rivers) on the eastern side; sockeye salmon primarily use lake systems high in the watershed; steelhead are found throughout the major headwater systems; and three to four types of chinook salmon occupy the mainstem channel and primary tributaries (Fulton 1970).

Chinook salmon were once distributed throughout the basin, but distinct stocks or run-types[2] occupied somewhat discrete regions (Fig. 1.4). Ocean-type, "fall run" chinook were concentrated in the lower watersheds west of the Cascade Mountains and in the mainstem Columbia east of the Cascades. Stream-type "spring run" chinook extended throughout the Columbia River Basin but were most commonly found in the Snake River watershed. "Summer run" chinook spawned and reared primarily in mainstem reaches of the Columbia east of the Cascade Mountains, particularly in the Snake River drainages.

Factors of Decline

Multiple factors both upriver and within the estuary have simultaneously contributed to Columbia River salmon declines since the middle of the 19th century (see timeline, Appendix). These include effects of harvest; loss and degradation of spawning, rearing, and migratory habitat; hatchery production; large-scale changes in the hydrology of the river and estuary; and natural climatic variability (NRC 1996).

Salmon Harvest--Fisheries for Columbia River salmon became well established within four decades after Bruno de Heceta's 1775 discovery of the river's outlet to the Pacific Ocean. Over a similar period of fishing activity, targeted salmon stocks (i.e., spring chinook) were already showing signs of depression. Commercial harvest of adult salmon began about 1818 with packing of salmon as a salted or pickled product, but increased dramatically with the advent of commercial canning in 1866.

In response to canner demand, harvest intensity increased rapidly starting in 1866 over an 8-year period (Lichatowich et al. 1996). Commercial fishermen initially targeted spring-run chinook, considered the superior canning variety. By 1890, the concentrated harvest of these fish

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[2] It is important when considering Columbia River salmon population and life-history structure to understand that our present-day characterization of "fall run," "spring run," and "summer run" stocks was the product of a terminology derived from the commercial fishery rather than a scientific differentiation of independently breeding populations. Recent genetic typing may improve our understanding of this complex stock structure.
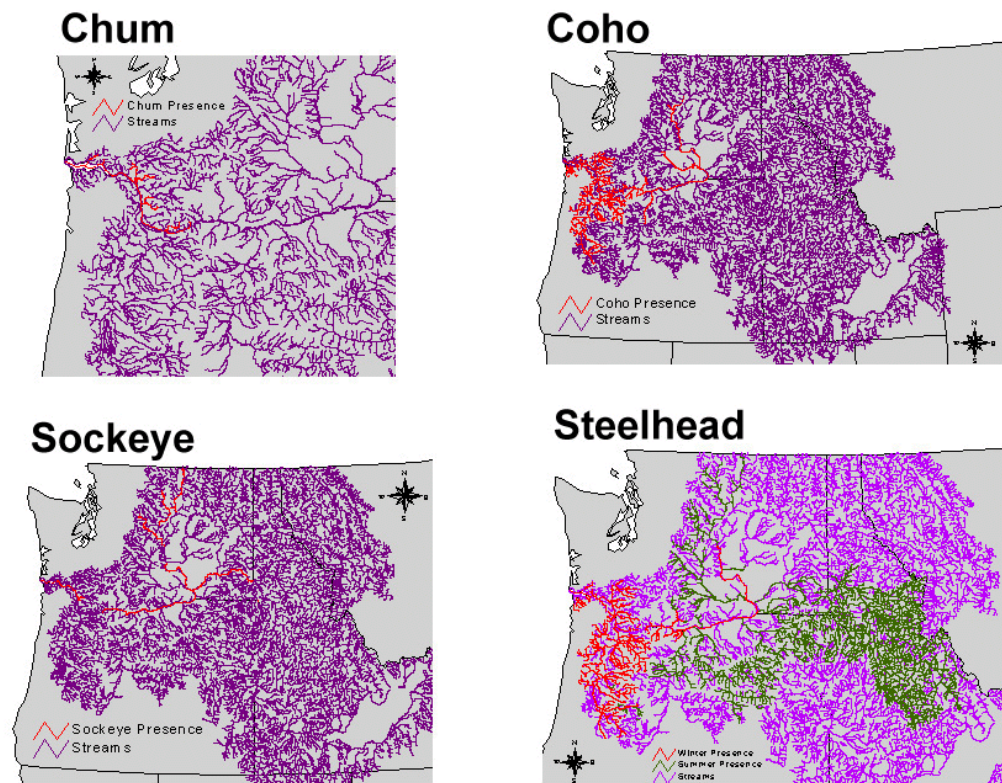
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Figure 1.3. Present distribution of four prominent species of Pacific salmonids in the Columbia River Basin (modified from Genovese and Emmett 1997).
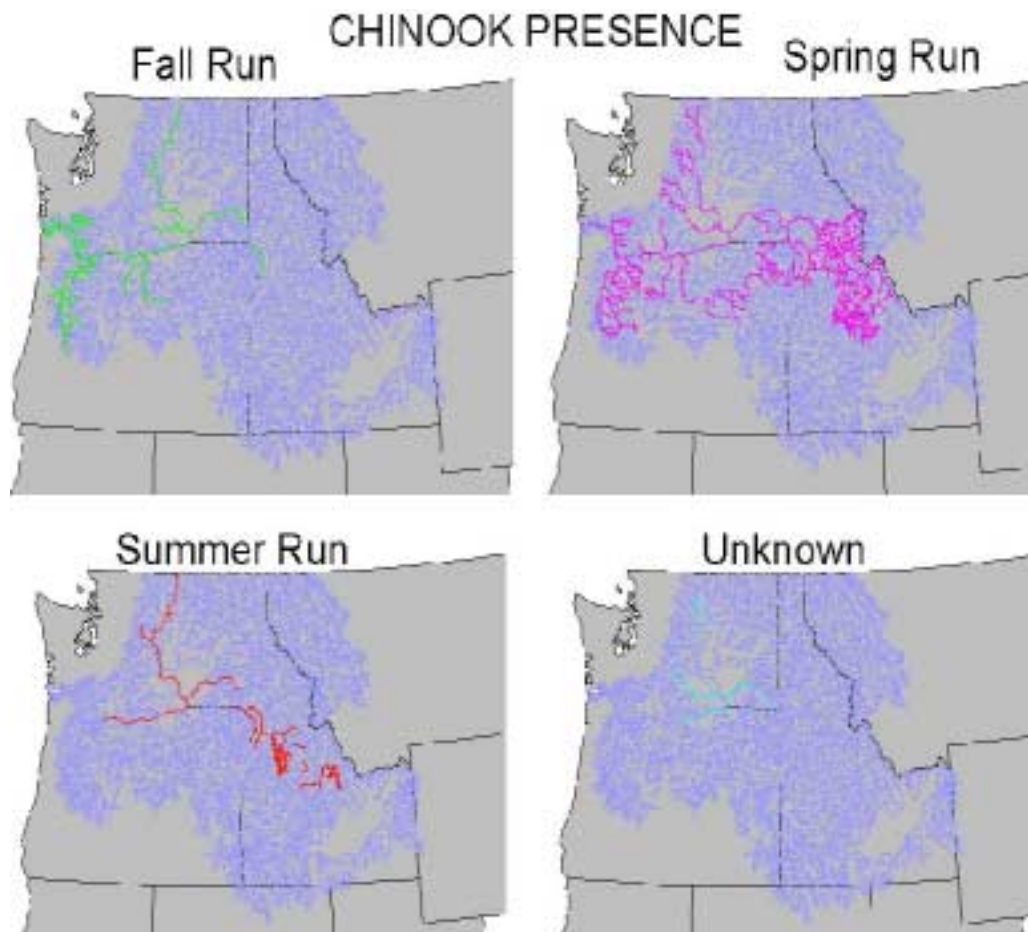
Figure 1.4. Present distribution of general run types of chinook salmon in the Columbia River Basin (modified from Genovese and Emmett 1997).

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in the estuary and lower river was blamed for the dramatic reduction in the number of adults returning to spawn in the Snake River Basin (Evermann 1895). Salmon populations had declined throughout the Columbia River system by 1911.

Changes in Freshwater Habitat--Although irrigation in the basin began about the same time as the development of industrial salmon fisheries, it did not increase substantially until after implementation of the Reclamation Act of 1902, which stimulated expansion of irrigated lands from 2,000 km^2 to nearly 40 x 10^6 km^2 today (NPPC 1986, NRC 1996). Yet surface water withdrawal did not accelerate until after World War II, principally in the mid-1960s, with technological advances and the availability of inexpensive electrical power. Irrigation not only decreased stream flow but also became a sink for migrating juvenile salmon that were diverted into irrigation canals and stranded in farmers' fields. As early as 1890, state fish commissioners reported substantial losses of juvenile salmon in irrigation networks in eastern Oregon (OSBFC 1890).

Extensive streambed and water modifications began to eliminate upriver spawning, rearing, and migratory habitats for salmon by the late 1800s. As early as 1894, mining in the Snake River watershed destroyed chinook spawning beds and was credited with the collapse of a popular Indian fishing site (Taylor 1999). Habitat loss due to logging and other intensive land uses such as cattle grazing increased after the turn of the century. Yet even before 1900, some practices damaging to salmon spawning and rearing habitat were prevalent, including removal of large woody debris from streams and the operation of splash dams (Sedell and Luchessa 1982, NRC 1996).

Construction of dams throughout the Columbia River Basin also has taken a heavy toll on salmon populations and accounts for much of the present-day reduction in historic salmon distribution (Fig. 1.2). Chinook salmon populations from the upper Columbia River Basin in British Columbia and Alberta, middle Snake River Basin and above, and the greater part of the Deschutes River Basin have been extinct for at least 40 years due to dams built without fish passage capabilities. Today, 23 major hydropower and flood control dams exist on the mainstem Columbia and Snake Rivers, and over 300 smaller dams are distributed on tributaries throughout the U.S. portion of the watershed (Fig. 1.5).

Salmon Hatcheries--Resource managers responded to declining Columbia River harvests in the mid-1890s by building salmon hatcheries. At first, hatcheries were promoted as a means to boost salmon production, to avoid the need for harvest regulations, and to generally improve on nature by using efficient technology to increase freshwater survival (Baird 1875, NRC 1996, Taylor 1999). Despite poor accounting for their performance and a general decline in support for hatcheries in the 1930s and 1940s, hatchery production expanded substantially in later years, stimulated by a new promise that artificial production could mitigate for the deleterious effects of dams and irrigation development (NRC 1996). Ultimately, more than 80 hatcheries were constructed in the basin (Fig. 1.5).
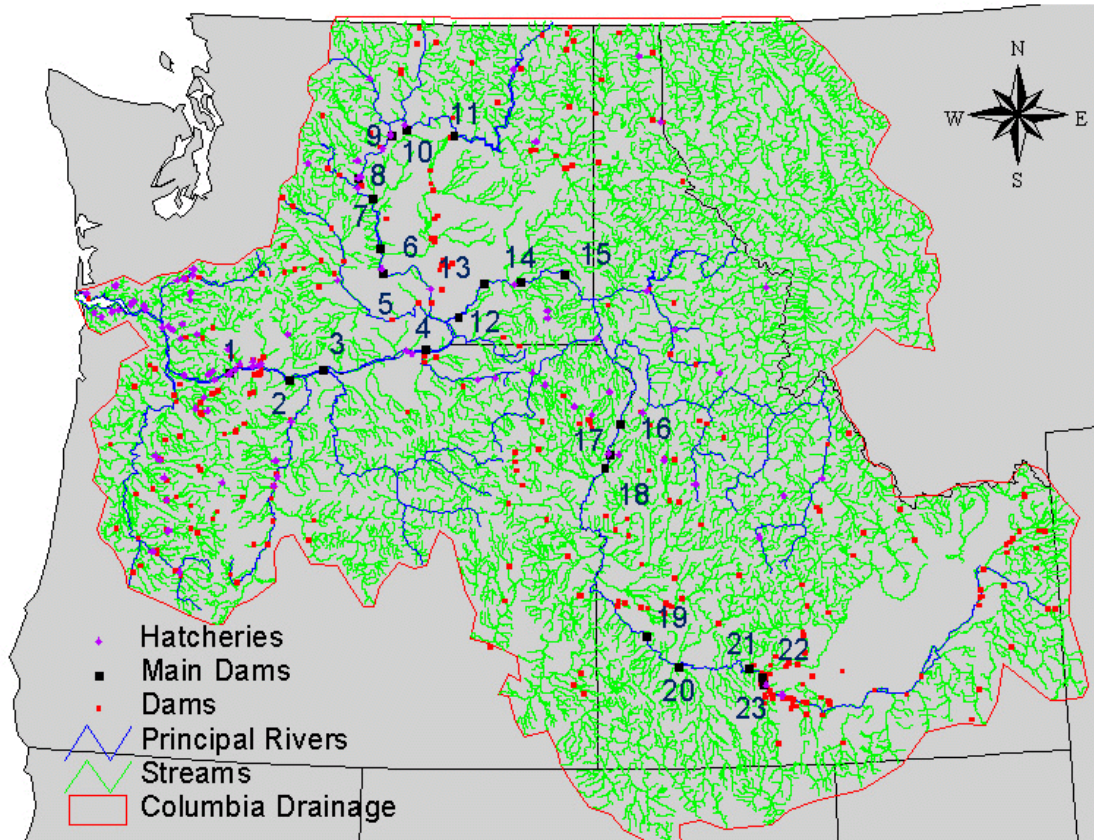
Figure 1.5. Present distribution of salmon hatcheries and mainstem and secondary dams along rivers and streams of the Columbia River Basin (modified from Genovese and Emmett 1997).

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Hatchery adults now comprise more than 95% of the coho, 70% of the spring chinook, about 80% of the summer chinook, more than 50% of the fall chinook, and about 70% of the steelhead returning to the Columbia River (CBFWA 1990, Genovese and Emmett 1997).

Hatchery influence on chinook populations is now greatest for fall chinook in the middle and lower Columbia River sub-basins (>85% of total juvenile salmon production (Genovese and Emmett 1997)), and for spring and summer chinook in the Snake and Salmon River sub-basins (90 to 100% of the total production, Fig. 1.6). More than 75% of the chinook salmon in the upper Columbia River, Deschutes, and John Day River sub-basins still results from natural production. On average, most hatchery fall chinook are released as fed fry and fingerlings, whereas releases of spring and summer chinook are more equally divided between sub-yearlings and yearling smolts (Fig. 1.7).

Significant natural production of coho salmon (~30% of the total) now occurs only in the lower Columbia River sub-basin (Fig. 1.8). Hatchery-reared coho are released both as subyearling fry and fingerlings and as yearling smolts (Fig. 1.9) but releases of unfed fry are rare except in the lower and middle Columbia River sub-basins (Genovese and Emmett 1997). Between 50 and 70% of the chum salmon now produced in the lower Columbia River sub-basin are released from hatcheries (Fig. 1.10) as fed fry or fingerlings (Fig. 1.11).

Intensive hatchery programs have had multiple effects on natural salmon production in the Columbia River Basin and on the recovery potential of at-risk populations (NRC 1996). Among these effects are reduced genetic diversity, competition between hatchery and naturally produced salmon, and depletion of wild populations in mixed stock fisheries. Loss of genetic and life-history diversity through large-scale hatchery production (Reisenbichler 1997) could be an important factor determining patterns of estuarine habitat use and the overall performance of juvenile salmon in the estuary.

Changes in the Estuary--Most loss and degradation of habitat within the Columbia River estuary occurred after the 1880s. Following a century of diking and filling activity, only 35% of the former area of marsh and swamp habitat remained in the estuary in 1980 (Thomas 1983). However, this is a gross estimate of the total habitat loss based on historical surveys. Other qualitative changes in physical conditions also may have had important effects on the salmon rearing capacity of the estuary.
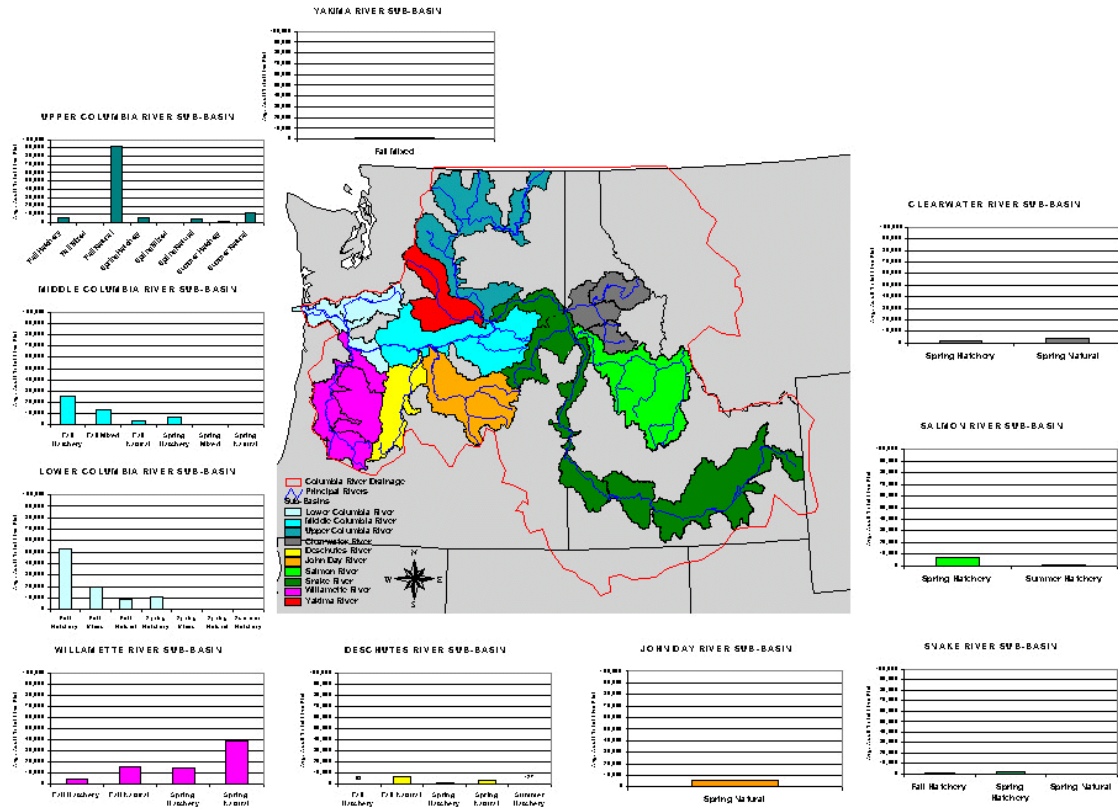
Figure 1.6. Average annual contribution (numbers of fish) of natural and hatchery production of spring and fall chinook salmon in 10 sub-basins of the Columbia River Basin (modified from Genovese and Emmett 1997).
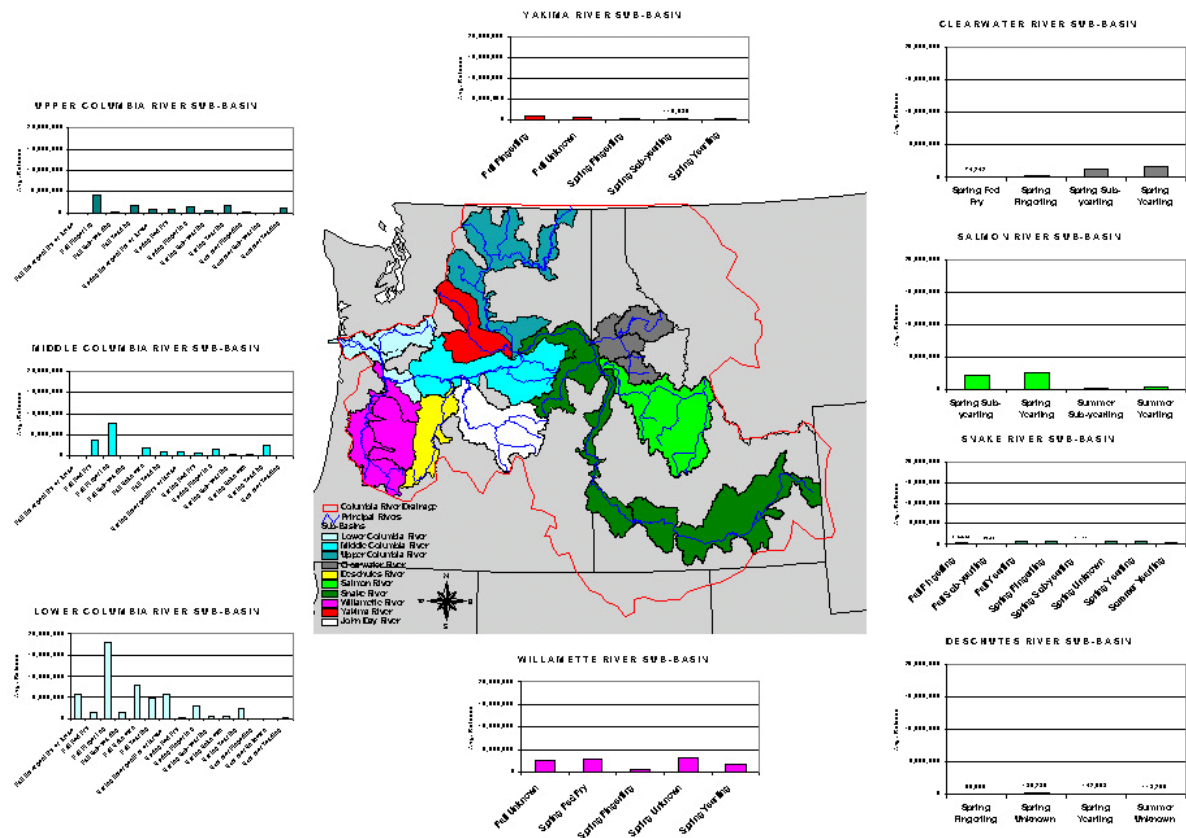
SARE draft: Estuarine Development

Figure 1.7. Average annual releases (numbers of fish) of hatchery-produced chinook salmon in nine sub-basins of the Columbia River Basin (modified from Genovese and Emmett 1997).
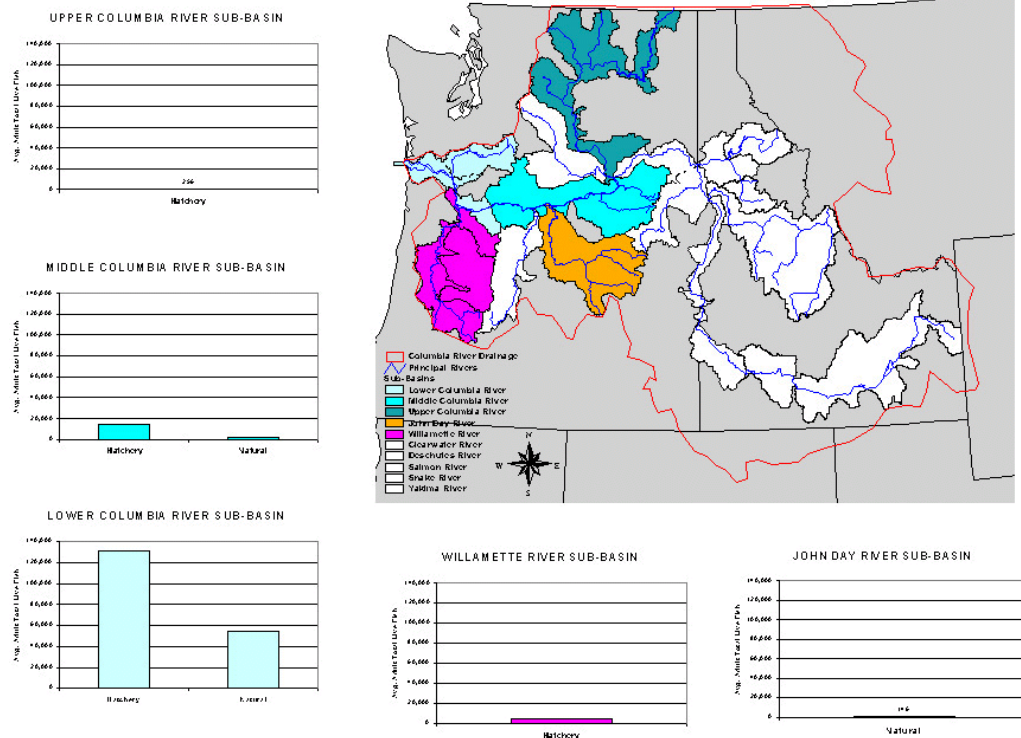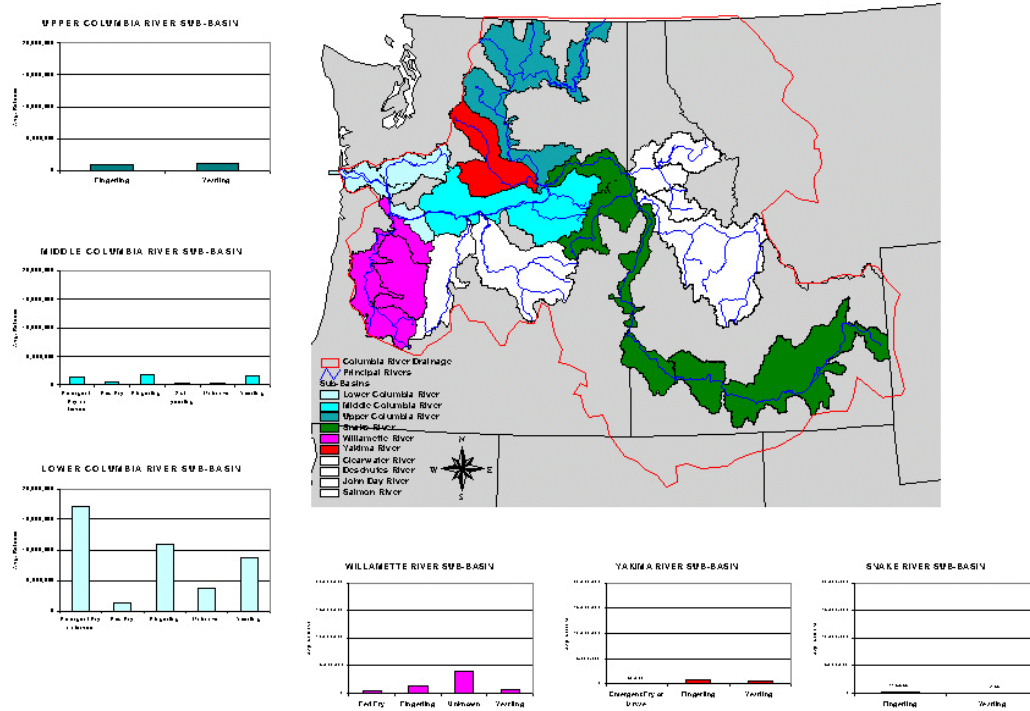
Figure 1.8. Average annual contribution (numbers of fish) of natural and hatchery production of coho salmon in five sub-basins of the Columbia River Basin (modified from Genovese and Emmett 1997).

SARE draft: Estuarine Development

COHO SALMON HATCHERY RELEASES

Figure 1.9. Average annual releases (numbers of fish) of hatchery-produced coho salmon in six sub-basins of the Columbia River Basin (modified from Genovese and Emmett 1997).
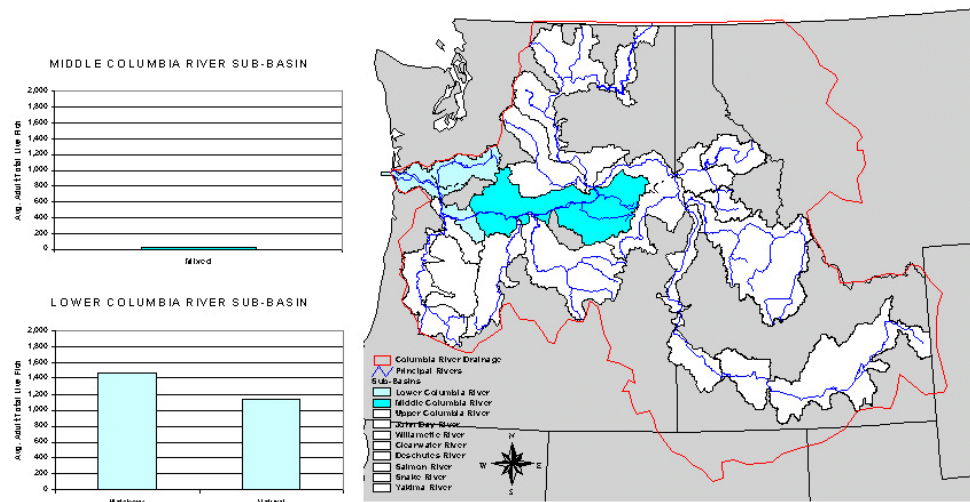
CHUM SALMON

Figure 1.10. Average annual contribution (numbers of fish) of natural and hatchery production to chum salmon in two sub-basins of the Columbi-a River Basin (modified from Genovese and Emmett 1997).
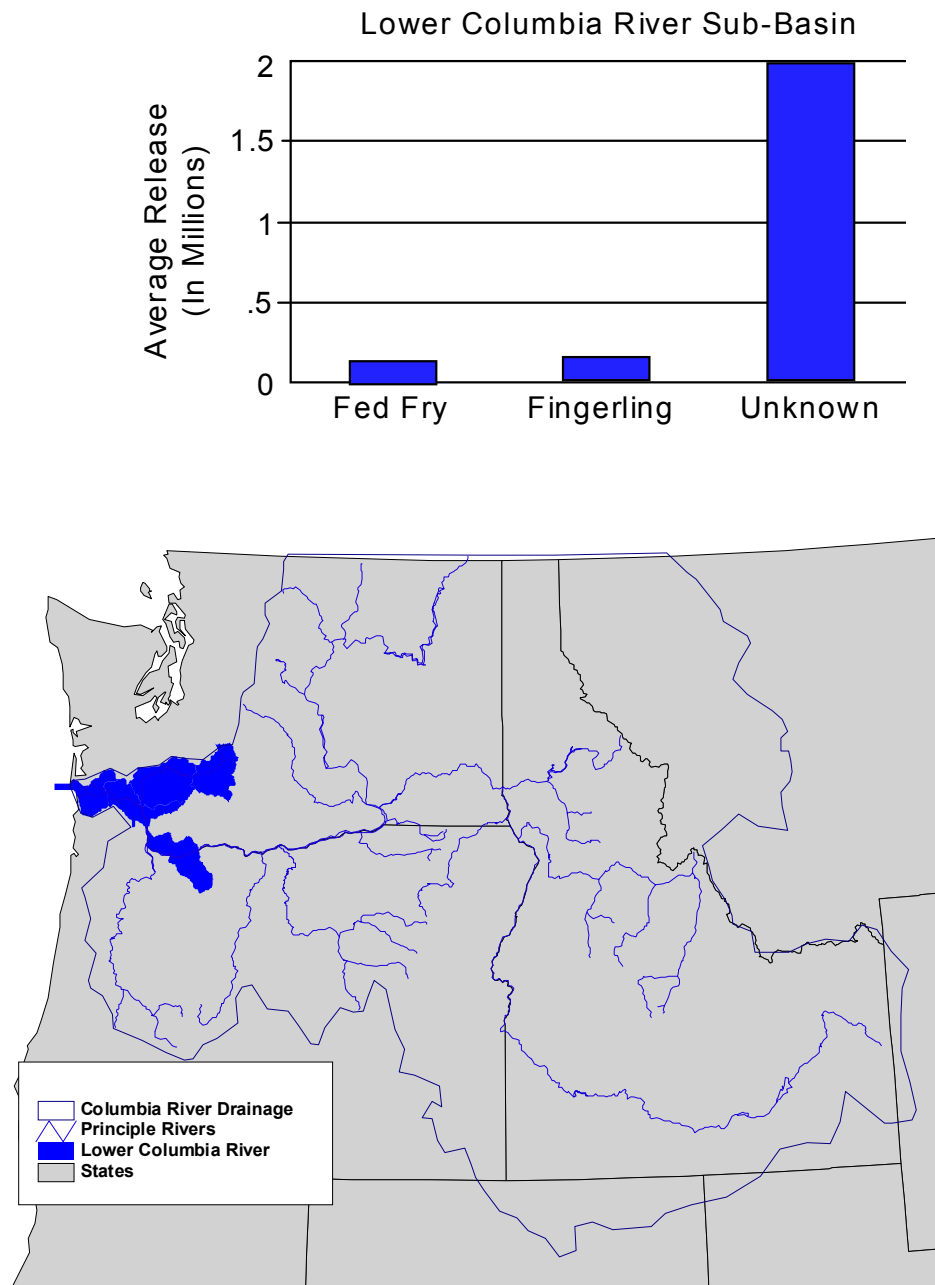
Lower Columbia River Sub-Basin

Figure 1.11. Average annual releases (numbers of fish) of hatchery-produced chum salmon in two sub-basins of the Columbia River Basin (modified from Genovese and Emmett 1997).

Shoreline armoring and construction of over-water structures, channel dredging and removal of large woody debris, channelization by pile dikes and other structures, and discharge of pollutants have all significantly modified estuarine habitats. Unfortunately, the effects of such alterations on either juvenile or adult salmon rarely have been assessed.

While early channel dredging and hatchery production began to alter estuarine conditions in the second half of the 19th century, it wasn't until well into the 20th century that channelization and filling removed considerable amounts of estuarine habitat, and hydropower and irrigation developments significantly altered river flows. By this time, salmon harvest was already in an obvious state of decline (Taylor 1999). Although there were at least 174 dams in the basin by 1936 (Appendix), many of the mainstem dams that would ultimately comprise the Columbia River hydropower system were not completed until the 1950s. Accordingly, significant, coordinated flow modifications did not occur until the late 1960s (Sherwood et al. 1984).

Climate Variability--Development activities in the Columbia River watershed and estuary were superimposed on a background of natural environmental changes, including substantial variations in climate, precipitation, and river flow (see Chapter 3). Often climatic fluctuations accounted for a greater degree of variation than those resulting from human interventions. Prior to 1910, spring freshets recorded at The Dalles often exceeded 20×10^3 m^3 s^{-1}, and winter flood flows in the Willamette River exceeded 5×10^3 m^3 s^{-1} (18 of 60 years). Both spring and winter peaks decreased dramatically thereafter, especially during the drought years of the 1930s (Sherwood et al. 1984).

Although the magnitudes of these changes are often impressive and suggest major shifts in riverine and estuarine disturbance regimes, Columbia River salmon stocks have withstood such disturbances for millennia (e.g., Chatters et al. 1995). Long-term productivity and the resilience of salmon species are the result of diverse life-history strategies that have evolved in a highly variable environment (Healey 1991, Healey and Prince 1995). A primary concern of recent salmon declines is whether habitat changes and reduced salmon diversity in the Columbia River Basin have severely undermined the capacity of populations to withstand large fluctuations, particularly major changes in long-established patterns of precipitation, temperature, and stream flow that some predictions suggest could accompany future global warming (Mantua et al. 1997; also see Chapter 4).

In conclusion--The cumulative effects of upstream developments on salmon rearing conditions in the estuary are poorly understood. Yet the combined influences of river flow regulation and industrial hatchery production are particularly noteworthy because of their direct impacts on salmon life histories or on the disturbance processes to which those life histories have adapted. Hydroelectric development now largely regulates the timing and magnitude of river flows, with potential effects on salmon migrations and on circulation processes and habitat conditions in the estuary. Hatchery programs now regulate the size, time of arrival, distribution, and rearing periods of most salmonids in the estuary. Thus, upriver controls placed on water and on fish have fundamental linkages to salmon production in the estuary.

History of Research in the Columbia River Estuary

Scientific and engineering research on the Columbia River estuary has been surprisingly modest given the river's social, cultural, economic, and strategic importance to the region (see timeline, Appendix). As described in Simenstad et al. (1990b), studies prior to 1980 tended to be fragmented, focusing on applied issues and target resources, rather than on a broader ecological understanding of the interactions among the estuary's physical environment, chemical structure, and biota. Early estuarine research projects were either engineering studies required for constructing the jetty or navigation channels or to compensate for depleted salmon runs. Although infrequent, fundamental studies of the timing and distribution of juvenile salmon during seaward migration actually began as early as 1914-1916, when Willis Rich conducted his first studies in the estuary (Rich 1920). With few exceptions, including McIssac's (1990) research on Lewis River fall chinook, studies have not attempted to link population structure and performance of upriver salmon stocks to their utilization of the estuary.

The richest source of information on juvenile salmon and their habitats in the estuary originates from studies conducted since the early 1970s by National Marine Fisheries Service (NMFS) biologists stationed at the laboratory at Hammond, Oregon. These efforts evaluated migration behavior of juvenile salmon and steelhead transported around hydropower dams (e.g., Dawley et al. 1978, 1981, 1985, 1986), dredging and dredged-material disposal impacts, particularly on the benthic biota (e.g., Durkin et al. 1979, 1981; Emmett et al. 1986; Hinton et al. 1990, 1992a,b), or stranding of juvenile salmon on beaches from ship traffic (e.g., Durkin et al.1977). Results for salmon, crab, and estuarine habitat characteristics in the Columbia River estuary were ultimately reported in the scientific literature (e.g., Durkin 1982, McCabe et al. 1983).

Scientific investigations of the spatial and temporal distributions of nutrients and biota and the supporting ecology of the Columbia River estuary are described by Haertel and Osterberg (1967) and Haertel et al. (1969). These complemented the results of comprehensive studies sponsored by the U.S. Atomic Energy Commission to determine the fate of radionuclides from the Hanford Nuclear Reservation (Pruter and Alverson 1972), providing a description of the estuary's physical and biological conditions.

The Columbia River Data Development Progam (CREDDP) studies during 1979-1980 (see Simenstad et al. 1990b for introduction to studies) stand out as perhaps the most noteworthy interdisciplinary examination of the estuary. While primarily descriptive, the CREDDP investigations provided the first real estimates of fundamental estuarine processes, including sediment accretion (shoaling) and productivity and trophic structure (Bottom and Jones 1990, Jay et al.1990, Jay and Smith 1990, Jones et al. 1990, Sherwood and Creager 1990, Small et al. 1990). Moreover, the CREDDP studies modeled estuary-scale circulation patterns (Hamilton 1990), quantified organic matter transfer through the estuarine food web (Simenstad et al. 1990a), and, for the first time, assessed effects of historical change on the estuarine ecosystem (Sherwood et al. 1990). Technical detailed reports of the CREDDP studies are summarized in a

technical synthesis by Simenstad et al. (1984) and in the scientific literature as a dedicated issue of *Progress in Oceanography* (1990, Vol. 25.).

In addition, the CREDDP studies supported the first extensive recovery of juvenile salmon below the tidal-freshwater reaches of the lower river. For the first time since the early work of Rich (1920), these efforts allowed estuarine residence times to be linked to freshwater early life histories (e.g., McIssac 1990). Coincidentally, the CREDDP studies also documented changes in the estuary from the May 1980 eruption of Mount St. Helens, including declines in juvenile salmon foraging efficiency (Emmett 1982, Emmett et al. 1991). Perhaps most significantly, the CREDDP studies inspired an ecosystem-process study of the ecological role of estuarine turbidity maxima with more than a decade of interdisciplinary research sponsored by the National Science Foundation's Land-Margin Ecosystem Research Program (see Simenstad et al. 1994 for general description).

Yet fundamental studies evaluating the links between juvenile salmon and estuarine conditions in the Columbia River are absent. Notably missing is information delineating:

1) specific (especially shallow-water) habitats utilized during rearing and outmigration through the estuary;

2) effects of physicochemical and biological conditions on estuarine residence times, growth, or survival;

3) food chain relationships (feeding and predation) among juvenile salmon, invertebrate prey, and vertebrate predators; and

4) differences in these estuarine habitat needs and ecological relationships among salmon species, life-history types, and source populations.

Until these rudimentary data are assembled, the "dependence" of juvenile salmon to estuarine conditions during their estuarine life history, and the relative impacts of historic changes in river flow, estuarine bathymetry, and other impeding factors (e.g., exotic species, predators) will remain speculative.

2. A CONCEPTUAL FRAMEWORK FOR EVALUATING ESTUARINE HABITAT CONDITIONS

Introduction

Considering the importance of the Columbia River Basin to salmon, the lack of information about their basic habitat needs in the estuary seems surprising. The Columbia River estuary is a huge system. Yet, with some exceptions (e.g., Levy and Northcote 1982), understanding of salmonid ecology is the result of studies of small estuaries undertaken within the last few decades (Reimers 1973, Healey 1980, Tallman and Healey 1994). While this research provides information about wild fry and subyearlings, much of what we know about salmon in the Columbia River estuary is based on larger yearling or fed subyearling fish released from hatcheries. As a result, we lack information about the specific life-support functions of the Columbia River estuary for salmon: ecological processes in much smaller estuaries may not apply directly to this large, river-dominated system, and the behaviors of hatchery fish in the Columbia may not represent the estuarine needs of naturally produced salmonids. Despite a few ecological surveys of fish assemblages and food chains (Haertel and Osterberg 1967, Bottom and Jones 1990), the estuarine life histories of diverse populations of salmon and the physical and biological processes that influence their estuarine habitats have rarely been investigated and are poorly understood.

What we do and do not know about the estuarine requirements of Columbia River salmon reflect certain underlying principles and assumptions in traditional fishery management. These concepts set limits on the kinds of information that were collected and also determined how that information was interpreted (e.g., Sinclair and Solemdal 1988, Lichatowich et al. 1996, ISG 2000). Traditional lack of interest in the estuary resulted in part from assumptions about the factors that regulate salmon production.

Recent concerns about the estuary, including recommendations that led to this evaluation (NPPC 1997), suggest a fundamental change in the conceptual approach to salmon ecology. These concerns are reinforced by numerous listings of Columbia River salmon stocks under the Endangered Species Act (Table 1.1), which emphasizes the importance of conserving biological diversity and the native ecosystems upon which this diversity depends. It is important that we understand the scientific basis for these changing ideas if we are to develop a satisfactory framework for this evaluation.

Fisheries science developed from an agricultural perspective of resource management (Bottom 1997). This perspective supported a progressive conservation philosophy that emphasized efficient production of natural resources for the benefit of all people. Science provided the methods and technologies to increase production of natural resources, compensate for losses to development, and provide for an equitable distribution of resources among all users (Bottom 1997, ISG 2000). To meet these utilitarian goals, resource management programs relied on a framework of scientific ideas we might call "production thinking." This perspective measured success by the output of natural resources (e.g., pounds or numbers of salmon, angler-days of use, etc.) and favored predictive methods and technologies to achieve production goals.

Production thinking emphasized short-term changes in the abundance of salmon populations, which were defined arbitrarily as any geographic unit of management interest (e.g., river basin, state, nation). From a production viewpoint, the term "population" was an abstraction defined by a particular management need or question.

Recent mandates to improve estuarine conditions and to protect life-history diversity in salmon (NPPC 1997) are derived from a different conceptual framework that was proposed explicitly to support salmon recovery programs in the Columbia River Basin (ISG 2000). This framework emphasizes continuity in consideration of the chain of freshwater, estuarine, and marine habitats that support salmon life cycles; it requires information about the life histories and evolutionary adaptations of salmon to their natural environments; and it places salmon survival at any one life stage in the context of the animal's prospective for success in navigating the entire habitat chain.

This long-term perspective is based on "population thinking," which defines populations as reproductively isolated and self-sustaining groups of animals within particular geographic areas (Mayr 1982, Sinclair 1988, Sinclair and Solemdal 1988). In contrast to the arbitrarily defined units of the production approach, this perspective views populations as functional reproductive units with distinct genetic and geographic characteristics (Kingsland 1995). Population thinking therefore raises new questions, for example, about the geographic structure of populations on the landscape and the specific habitats that support them.

A primary challenge for our analysis was how to answer questions about estuarine habitats and salmon recovery, which require a geographic and evolutionary perspective (ISG 2000), when most of the available information has been collected and interpreted from a production view. To establish a conceptual framework appropriate for the objectives of this evaluation, we first reviewed the underlying assumptions applied to past salmon research and management in Northwest estuaries. Specifically, we contrasted ideas from estuarine studies that were based on production thinking from those based on population thinking. We then examine a theory of populations derived from marine fish ecology as a starting point for the conceptual approach and the specific analyses we have chosen for this assessment.

Historical Perspectives on Salmon in Estuaries

Production Thinking in Estuarine Research

Although in recent years, the traditional assumptions of fisheries management have received increased scrutiny (McEvoy 1986, Finlayson 1994, Lichatowich 1999, ISG 2000), the impact of these ideas on salmon research and management in estuaries has not been examined specifically. Lack of research interest in Northwest estuaries stems, in part, from long-held assumptions that populations are regulated by "density-dependent" interactions–biological factors like predation, disease, or food

competition–during the earliest and presumably most vulnerable stages of salmon life. These ideas coincided with the freshwater habitats where salmon are most easily observed and where the sources of mortality can be controlled.

Salmon hatcheries, for example, developed from the assumption that adult abundance is limited by freshwater mortality, and that abundance increases in direct proportion to the number of additional eggs that survive when they are reared in a controlled environment (Lichatowich 1999). Theoretical models in population ecology and the concept of "maximum sustained yield" similarly assumed density-dependent control of salmon and developed equations to describe the apparent relationship between population size and the resulting number of recruits (e.g., Ricker 1948, Larkin 1977).

Salmon hatcheries and harvest models have had widespread appeal. They reinforced the fundamental economic view of fishery management (Bottom 1995, 1997). They also met new standards of scientific legitimacy, as modern ecology actively shunned historical and descriptive explanations for the reductionist and predictive methods of the physical sciences (Kingsland 1995). Both achieved this predictability by simply eliminating natural variation: hatcheries through technological control of the only (fresh-water) variations assumed to be important, and harvest models by averaging the apparent relationship between population size and recruitment over the period of observation (Cushing 1995). In both cases, the assumption that populations are regulated by a predictable, freshwater struggle for existence allowed fishery management to avoid the messier stages of the salmon life cycle that were more difficult to understand and much more difficult to control.

This is not to say that the estuarine life of salmon has been ignored altogether. But even when the estuary has been considered, management and research activities often simply extended to tide water the same agricultural ideas used to remove production constraints upriver. For example, after the turn of the century, state fish commissioners sought legislative support and later successfully established bounties for marine birds and mammals under the assumption that large numbers of estuarine predators constituted a significant "waste" of an economic resource and, therefore, should be destroyed (e.g., Reed 1901). Later, when hatchery technology had developed the means to rear salmon for extended periods and control most of their freshwater mortality, fishery managers looked for ways to further protect their investment by eliminating other perceived threats immediately below the hatcheries.

In the late 1940s, Gharrett (1955) transferred groups of hatchery chinook and coho fingerlings directly into Oregon's Nehalem River estuary to test whether the procedure could be used to avoid instream competition with wild fish, predation during downstream migration, and the expense of holding subyearling fish in hatchery ponds until their second spring. A few decades later, similar ideas were implemented on a larger scale when the Oregon State Game Commission constructed an estuarine impoundment for holding salmon fry in Lint Slough in Oregon's Alsea River estuary (Raynor and Garrison 1965, Garrison 1966, Holm 1969). By regulating tidal and river

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flows and trapping nutrient-rich ocean water in the shallow slough, fishery managers hoped that salmon would thrive on a rich estuarine prey base, eliminating hatchery food costs, increasing growth rates, and protecting fish from both riverine and estuarine predators (Holm 1969, Bottom and Simenstad in press).

Declining salmon runs in the late 1970s highlighted the failure of traditional hatchery operations to maintain or increase salmon returns and raised new questions about whether estuaries themselves might be "bottlenecks" to production. Based on the apparent success of Japan's massive chum salmon production program, several large U.S. corporations developed ocean ranching facilities with salmon release and recapture sites located near the mouths of several Oregon estuaries. Researchers began monitoring potential interactions between private hatchery and wild juveniles, concerned that hatchery-released fish might not migrate directly to sea and could compete with wild, estuarine-rearing salmonids (Nicholas et al. 1979, Myers and Horton 1982, Nicholas and Herring 1983, Nicholas and Lorz 1984). Some initiated "carrying capacity" studies to estimate the quantities of hatchery chinook salmon that estuaries could support (Reimers et al. 1979, Nicholas and Downey 1983, Nicholas et al. 1984).

Finally, to directly test the estuary-bottleneck theory, researchers conducted experiments to compare smolt survival of hatchery coho and chinook salmon released in-river and barged various distances offshore of the Columbia (Solazzi et al. 1991) and Fraser River estuaries (Macdonald et al. 1988, Levings et al. 1989). Reminiscent of the early experiments that moved fish to the estuary to eliminate potential in-river mortalities (Gharrett 1955, Raynor and Garrison 1965, Garrison 1966), these experiments tested whether salmon are truly "estuarine dependent" or whether survival could be increased if salmon simply avoided the estuary altogether.

Much research in the Columbia River estuary today remains a downstream extension of upriver ideas to control salmon production and mitigate for effects of the hydropower system. Some estuarine studies are designed around fish tagging technologies and the incidental availability of experimental groups of marked fish used to evaluate hatchery rearing practices, barging operations for transporting fish around dams, and the relationships between river flow and fish passage through the dams. For example, the National Marine Fisheries Service has long maintained a monitoring site at Jones Beach to provide a tidewater recovery point below Bonneville Dam where migration timing, travel times, and survival for various groups of marked salmon can be estimated to the upper estuary (e.g., Dawley et al. 1986). Ongoing research on salmon predation by Caspian terns (Roby et al. 1998, Collis et al. 1999, USACE 1999, Ryan et al. in press) similarly relies on estuarine recoveries of PIT-tags from fish marked upriver, extending to the estuary earlier concerns about fish predation below mainstem dams and in the reservoirs (e.g., Beamesderfer and Rieman 1988, Beamesderfer at al. 1990, Rieman and Beamesderfer 1990).

Yet it is unclear how the migrations, rearing requirements, or survival of estuarine salmonids should be interpreted from various upriver tagging studies. The probabilities

of recapturing marked fish at Jones Beach or recovering tags at a tern colony in the lower estuary depend on the numbers and characteristics of individuals chosen for numerous upriver experimental groups. Marked fish do not represent the full diversity of sizes, geographic origins, or life histories of juvenile salmonids throughout the basin. Estimates of travel times or predation rates for marked fish may not apply to those of smaller subyearlings that are most likely to rear in the estuary for extended periods but are least likely to be tagged upriver.

Because the design of these studies is dictated by the sampling opportunities that are created by hatchery, tagging, and recapture technologies--opportunities that emphasize relatively large hatchery fish with yearling life histories--it is unlikely the results apply similarly to all juvenile life-history types in the estuary. Most importantly, results for tagged hatchery fish, even if they do represent behaviors of the majority of individuals that are now produced in the Columbia River ecosystem, shed little light on the historical habitats or life-history types that have been lost and that a successful recovery program ultimately may need to re-establish.

In summary, one common theme of production thinking in salmon management is the notion that estuaries, like rivers (Lichatowich 1999), are hazardous places. A primary goal of production-oriented research is to identify, eliminate, or simply avoid apparent ecological constraints, particularly any obvious predators or competitors in the estuary. This approach emphasizes the need to reduce estuarine mortality of juvenile salmon regardless of their geographic origins or life histories or whether any of the additional survivors would be destined to return as adults. Most importantly, because it focuses on presumed threats to salmon, production thinking provides little or no information about the estuarine habitats and conditions that salmon actually *need*. Instead, the estuary is seen as a corridor through which a single, large, and undifferentiated mass of fish must run a gauntlet of predators before they can escape to the ocean. Among the many assumptions inherent to this view are the following:

• The factors that limit salmon production in estuaries are separable from conditions experienced during other life stages and can be treated independently.

• Estuaries have significant excess carrying capacity to accommodate large releases of hatchery fish (ISG 2000).

• Estuarine abundance of juvenile salmon is regulated "top-down" by predators (or sometimes "bottom-up" by competitors) through density-dependent processes.

• The number of adult salmon produced each year is a function of the rate of predation (or competition) that occurs in the estuary.

• To avoid predators or competitors and improve survival rates, salmon must move rapidly through the estuarine corridor.

- Adult returns will increase in proportion to the number of estuarine predators or competitors that are removed or otherwise prevented from interacting with salmon.

Population Thinking in Estuarine Research

Not all research in the Columbia River estuary has taken a strictly production-oriented view of salmon. In fact, the first significant study in the estuary (Rich 1920) was a descriptive survey to understand chinook salmon biology and life history in the Columbia River Basin. This survey began as an outgrowth of Gilbert's (1913) early studies of sockeye salmon in British Columbia rivers where he devised methods for interpreting salmon life histories from the patterns of circuli recorded on their scales.

Rich's (1920) research was not an estuary study per se; it was a survey of the periods of migration, sizes, and ages of juvenile salmon migrants as they moved through the main river and estuary toward the ocean. To interpret the migration behaviors he found in the estuary, Rich looked upstream. For example, despite a comparatively short period of spawning for chinook salmon throughout the basin, Rich found young salmon of a wide variety of age and size classes moving downstream and through the estuary throughout the year. From the distinct rearing histories recorded on the salmon scales, he inferred that this continuous estuarine migration was the sum of many independent populations whose separate movements and rearing patterns reflected different climatic and environmental conditions across the basin. For fish that remained in brackish water, Rich also documented from scale patterns a significant increase in growth rate relative to growth in fresh water, suggesting improved rearing conditions in the estuary.

Significantly, Rich's (1925, 1927) continued research on adult salmon in the Columbia River Basin provided much of the information he used to finally demonstrate that salmon indeed return to their home streams to spawn. He thus concluded that each salmon species is composed of a large number of local, self-perpetuating populations, whose behaviors are molded by the particular sets of conditions found in their spawning and nursery areas (Lichatowich 1999). These results later contributed to Rich's (1939) ideas for an entirely new management approach that defined each population and its associated watershed as the fundamental unit of salmon conservation.

The population ideas that Rich (1939) developed from empirical observation thus defined a very different kind of estuary from the one envisioned based on production thinking (Table 2.1). Rather than a simple corridor through which a single, homogeneous group of outmigrants move as rapidly as possible to avoid voracious predators, Rich's estuary was a complex nursery ground where a continuous stream of individuals from geographically discrete populations converged and remained for varying periods of time.

Table 2.1. Contrasting views of salmon conservation in estuaries based on production and population thinking.

	Production Thinking	**Population Thinking**
Goals	Efficiency, production	Resilience, reproduction
Population Units	Arbitrarily defined	Biologically defined
Time Frame	Short	Evolutionary
Objectives	Control survival and abundance	Conserve local populations and life-history diversity
Estuary Function	Corridor for a single, homogeneous group of salmon	Nursery area for many self-sustaining populations
Estuary Management	Control predators, promote rapid salmon out-migration	Protect habitats of diverse life-history types

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From this perspective, diverse salmon rearing behaviors in the estuary became linked to habitats upriver where self-sustaining populations spawned and reared.   Thus, a fundamental implication of population thinking is that *estuarine habitat use and salmon migration patterns may depend as much on the status of upriver habitats and source populations as on the environmental conditions within the estuary itself.*

In the last few decades, population thinking has played a significant role in understanding the estuarine ecology of salmon, particularly in some smaller Northwest estuaries (e.g., Reimers 1973, Carl and Healey 1984, Healey 1982, Simenstad et al. 1982). Yet, ironically, these ideas have had little influence on research in the Columbia River estuary since the 1930s, despite the fact that this system provided much of the early data from which population thinking and the entire stock concept of salmon conservation developed in the first place (Rich 1939, Ricker 1972).

By this time, hydroelectric and irrigation development in the Columbia Basin had shifted attention back to the more familiar production approach which emphasized the development of hatchery, fish bypass, and transportation systems to compensate for upriver habitat and population losses (Lichatowich 1999). Despite the implications of Rich's early population studies, and except for occasional concerns about estuarine predators and competitors, the expanding business of fish production had little interest in the estuary.

A Theory of Populations with Complex Life Cycles

Marine ecologists have become increasingly aware that species with complex life cycles--distinct developmental stages located in spatially discrete habitats--may be regulated by ecological processes coupled among different environments. For example, Roughgarden et al. (1988) note that marine rocky intertidal communities at some sites are regulated by adult interactions and competition for space, while at other sites, distant ocean currents and upwelling processes control populations by limiting the larval supply. Thus, traditional stock-recruitment approaches may not adequately describe the dynamics of marine populations with complex life cycles, whose transport or migrations link processes in distant habitats, and whose survival can be regulated by physical processes unrelated to population density.

The migrations of anadromous salmonids similarly integrate processes across vastly different aquatic environments. Recent research indicating that salmon production is regulated by large-scale shifts in the North Pacific Ocean and atmosphere (Francis and Sibley 1991, Beamish and Bouillon 1993, Mantua et al. 1997) contradicts traditional ideas that density-dependent interactions during the earliest life stages are sufficient to explain salmon variability. The role of density-independent processes in salmon production may be particularly important in the California Current region, which is

considered a physically controlled ecosystem, wherein plankton assemblages and carrying capacities are regulated by ocean currents and upwelling rather than biological interactions (McGowan and Walker 1993).

Climatic shifts in the North Pacific not only influence marine survival of salmon but also control processes at all other stages of the salmon life cycle by modifying, for example, flow and temperature conditions upriver and salinity gradients and sediment transport in estuaries (e.g., Greenland 1994, Melack et al. 1997). A framework for understanding salmon variability must account for freshwater, marine, and estuarine processes that are linked through salmon migrations.

One approach that may be useful for understanding the role of estuarine habitats for salmon is Sinclair's (1988) "member-vagrant" hypothesis, which proposes a set of general principles for understanding the dynamics of marine species with complex life cycles. Unlike the production focus of traditional fishery management, Sinclair's hypothesis uses population thinking to simultaneously account for four characteristics of marine populations: differences between species in population richness, the geographic patterns of populations within species, control of absolute (e.g., mean) abundance, and control of population variance. The member-vagrant hypothesis provides a useful perspective for evaluating the specific needs of salmon within estuaries while placing these needs in context of the entire continuum of habitats needed to sustain salmon life cycles.

Population Pattern and Richness

The member-vagrant hypothesis states that *the pattern and richness (diversity) of populations are determined by the number and location of geographic features where a species' life cycle can be brought to closure* (Sinclair 1988). According to this idea, complex life cycles of marine populations have evolved in response to certain persistent features in the environment that allow sexually reproducing individuals to find a mate with a similar genome. Because membership in a population (e.g., successful reproduction) requires that individuals be in the right place at the right time, certain geographic features provide a predictable setting where organisms of reproductive age can converge at an appropriate time in otherwise diffuse and dispersive aquatic environments.

Life histories of marine and anadromous species thus involve transport and migration behaviors that are linked to particular geographic features including streams, estuaries, offshore banks, currents, ocean gyres, and upwelling systems. Thus, Sinclair's hypothesis suggests that the number of geographic settings allowing a species to successfully complete its life cycle determines the number of its component populations.

According to this idea, marked differences in population richness among marine species are associated with the number of various egg and larval retention areas around which the life histories of populations have become adapted. For example, at the low end

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of the spectrum is European eel (Fig. 2.1), which consists of one panmictic population whose egg and larval retention area is the entire North Atlantic Gyre (Sinclair 1988). The greater richness and geographic patterns of Atlantic herring populations, on the other hand, result from a series of discrete larval retention areas maintained within coastal embayments, estuaries, and certain tidal circulation features of open-ocean spawning grounds.

The most population-rich of Sinclair's examples is Atlantic salmon, which, like Pacific salmon, have a diverse population structure defined by the number of streams and rivers flowing into the ocean and to which adults home for spawning. Precise homing allows even populations in adjacent streams to become isolated and adapted to local conditions (Miller and Brannon 1981, Carl and Healey 1984). Common to these examples is the segregation of early life stages among population groups and the inter-population mixing during later stages. Differences among species in population richness are explained by this separation of populations during the early life stages based on the same specific geographic features to which adults home to reproduce.

A critical underpinning of the member-vagrant hypothesis is the interaction between physical geography and the behavior (e.g., life histories) of individuals that "use" various persistent features of aquatic systems to maintain membership in a population. For example, the vertical migration behaviors of many zooplankton and pelagic stages of benthic invertebrates are adapted to the two-layered, estuarine tidal circulation, which aids their retention in estuaries and minimizes individual losses from populations (Sinclair 1988). Such interactions between physical geography and behavior similarly characterize the anadromous life cycles of Pacific salmon.

Diverse salmon life histories that include broad variations in timing and size of seaward-migrating fish, as well as in periods of estuary residence, represent alternative time/space "solutions" for completing anadromous life cycles within the overall distributional range and physiological constraints of each species. Distinctions in migration timing, size, and rearing periods are linked to fine-scale features within each aquatic environment (stream, river, estuary, ocean) where salmon seek refuge, feed, and delay their passive seaward transport for varying periods as needed to complete each developmental stage (egg, fry, smolt, adult). Strung together, the physical features in each environment and at each ontogenetic stage constitute a chain of habitats in time and space that salmon "navigate" to complete their life cycles and maintain membership in a population.

The habitat chains of diverse salmon species and populations include a variety of low-velocity refugia and feeding habitats where energy is dissipated and organic matter and food resources are retained in high-energy aquatic environments. Among the various "retentive structures" that allow salmon to delay their downstream displacement and meet their developmental needs are undercut banks, pools, and beaver ponds in tributary
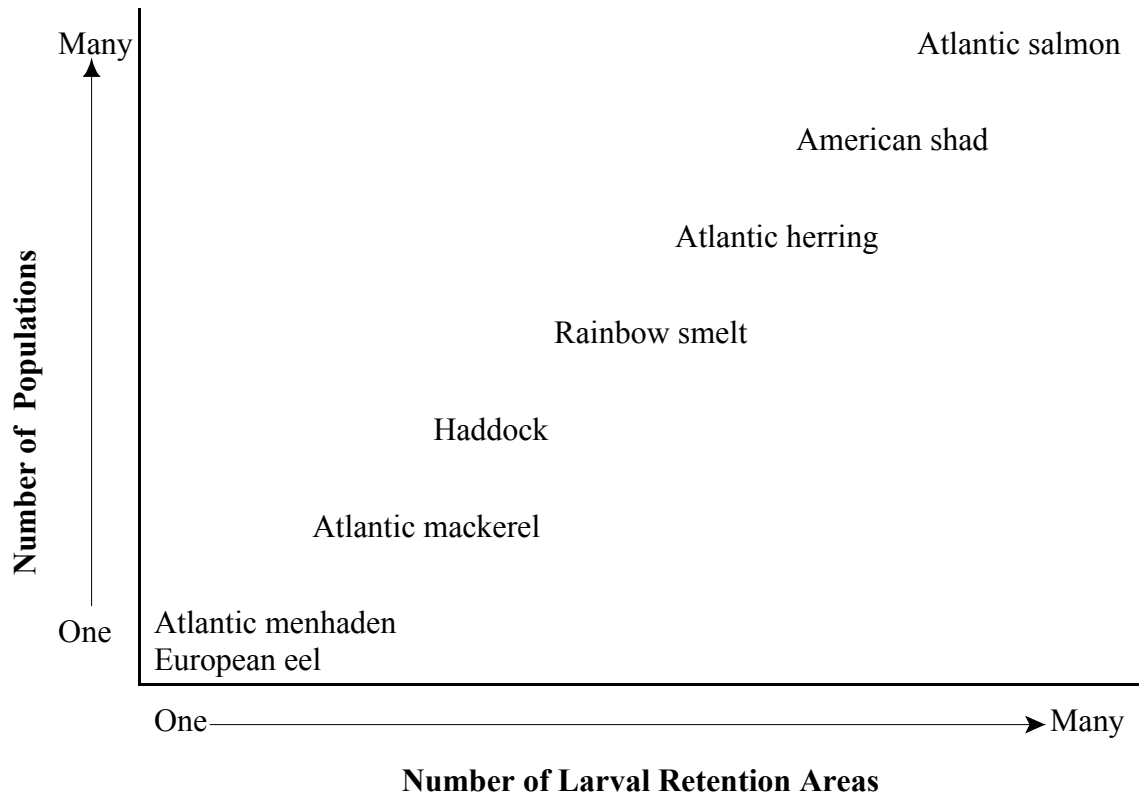
Figure 2.1. The continuum in population richness of selected anadromous and marine species in the northern Atlantic (from Sinclair 1988).

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streams; large woody debris, off-channel alcoves, and floodplain forests in larger streams and rivers; shallow wetlands, marsh channels, and sloughs within estuaries; and perhaps upwelling fronts, the Columbia River plume, and the Alaskan Gyre in the North Pacific Ocean.

Abundance and Variability

A second important component of the member-vagrant hypothesis is the assumption that *temporal variability in abundance is determined by the loss of individuals from the area that ensures membership within a given population* (Sinclair 1988). According to this idea, loss of members from a population ("vagrancy") occurs throughout a life cycle and may be the result of biological interactions or purely physical (geographic) factors. Sinclair distinguishes what he calls *spatial* processes, which involve geographic displacement from the area and time necessary to ensure population membership, from *energetics* processes, which include mortality from predation, competition, or disease. Spatial losses, for example, may result from advection of individuals away from the area/time necessary to complete their life cycle. Such losses do not necessarily require mortality of individuals but simply the failure to successfully find a mate or reproduce within the appropriate area and time.

For example, adult salmon vagrants ("strays") include individuals that return to spawning grounds outside their natal stream. Some level of straying may be evolutionarily advantageous, allowing species to "test" new environments, increase genetic heterogeneity, and expand their range or recolonize habitats destroyed by disturbance. On the other hand, many strays may simply not contribute to the next generation because they fail to find a mate at the precise time or place of return or because their genetic patterns of emergence, rearing, and migration are mismatched for the conditions represented in a new environment. For example, using electrophoretic analysis, Tallman and Healey (1994) estimated that gene flow among chum salmon populations in Vancouver Island streams was less than 5%, although straying rates estimated from tagging studies were considerably higher, as much as 46% in one instance. These results suggested that most strays to non-natal streams did not successfully reproduce.

Both spatial and energetics losses may involve either density dependent or independent processes. However, the member-vagrant hypothesis suggests in principle that spatial processes alone can be sufficient to account for density-dependent losses from a population. For example, the size of the geographic area capable of maintaining members of a population determines its carrying capacity and controls fish density (Sinclair 1988). This mechanism has been suggested to explain strong year classes of sardines off Japan, for example, when oceanographic changes expand the total area available for successful spawning and prey production and increase the survival of post-larvae (Lluch-Belda et al. 1992).

Climatically driven expansion or contraction of the ocean habitat area suitable for survival might also be important for salmon in the Pacific Northwest, which is located near the subarctic boundary of the North Pacific Ocean and encompasses the southern edge of the range of several salmon species (Fulton and LeBrasseur 1985, Bottom et al. 1998).

Applications of the Theory to Salmon and Estuaries

The member-vagrant hypothesis has a number of important implications for understanding the structure and dynamics of salmon populations. First, if the hypothesis is correct, then salmon populations and life history types should exhibit a geographic structure associated with the varied features and characteristic patterns of variability encountered across their broad distributional range.

Second, such a complex life-history structure should maximize productivity and resilience of salmon by diversifying habitat use and spreading risks unevenly in time and space. Third, unlike traditional population theories, the hypothesis suggests that a variety of geographic and density-independent processes throughout all stages of the salmon life cycle might explain fluctuations in population abundance. The following evidence offers support for these conclusions and suggests that Sinclair's (1988) hypothesis can provide a general framework for evaluating the role of estuarine habitats in salmon life cycles.

The Geographic Structure of Populations and Life Histories

Biologists have frequently documented examples of the complex geographic structure of salmon populations and described considerable life-history diversity within and among populations (e.g, Taylor 1990, Healey and Prince 1995) consistent with the patterns we would expect from Rich's (1939) observations and Sinclair's (1988) hypothesis. Yet the importance of this geographic structure to observed patterns of estuarine residency and habitat use has rarely been considered in salmon research and management. Nonetheless, results from several population studies in the last few decades support the member-vagrant hypothesis and its application to salmon in estuarine environments.

Perhaps the best example is a detailed study of chinook salmon life histories in Sixes River, Oregon. Within this small watershed, Reimers (1973) documented five different life-history types of chinook salmon based on the patterns of seaward movement by juveniles (Table 2.2). By comparing migration and rearing patterns of outmigrants with those recorded on the scales of returning adult salmon, Reimers found approximately 90% of the fish returning to spawn were Type-3 fish: those that had spent an extended period of time rearing in the estuary in late summer where they grew to a large size before migrating to the ocean. Yet this was not the most abundant pattern among the juveniles he sampled.

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Table 2.2. Juvenile life-history types for chinook salmon in Sixes River, Oregon (from
Reimers 1973).

- Type 1: Fry move directly to sea within a few weeks

....

- Type 2: Juveniles stay in the river or tributaries until early summer, move to the
estuary for a short period, and go to sea before late summer

....

- Type 3: Same as above except fish stay in the estuary through late summer and go
to sea in the autumn

....

- Type 4: Juveniles stay in tributaries until autumn rains and then migrate to sea

....

- Type 5: Juveniles stay in tributaries through the summer, rear in the main river the
following spring, and enter the ocean as yearlings

Although Reimers' (1973) results are often cited to demonstrate that extended estuarine rearing and growth are critical for chinook salmon, it is likely that if he had studied several broods of chinook, he might have found other life-history types that survived equally well during other years and environmental conditions. This possibility is supported by an experiment that compared the survival of Campbell River juvenile chinook released over three brood years into four different environments: the river, the estuary, an offshore transition area, and the ocean (Macdonald, et al. 1988, Levings et al. 1989). Although fish with access to the estuary (groups released upriver or directly in the estuary) had a higher survival to return during the first two years of the experiment, in the third year, survival was about the same for all four release groups. Thus, changing environmental conditions from year to year may favor different rearing and migration behaviors within a river system.

In the Nanaimo River, British Columbia, Carl and Healey (1984) identified three juvenile life-history types for chinook salmon associated with differences in their age of seaward migration, including subyearling estuarine smolts (fry move directly to the estuary and enter the ocean in June or July), subyearling riverine smolts (fry rear in the river two months and briefly in the estuary before entering the ocean), and yearling riverine smolts (juveniles stay in the river a full year and move seaward in the spring). Genetic isolation of the three life-history types was suggested by variations in allozyme frequencies and differences in body morphology of each type. From these results, they concluded that variations in migration behavior within the Nanaimo River Basin are linked to different subpopulations associated with geographically distinct spawning areas. Thus, as suggested by the member-vagrant hypothesis, subpopulations have developed around specific geographic settings where different groups of salmon complete their life cycles through different times and ages of migration.

The present-day distribution of chinook salmon in the Columbia Basin also reveals a geographic structure of spawning populations and juvenile life histories, although it is a fragmented remnant of the mosaic of spawning races and life-history types that once existed (ISG 2000). Today, stream-type (yearling migrant) life histories are most common in headwater streams of the Columbia River and in the Snake and Salmon River subbasins, while ocean-type (subyearling migrant) life histories predominate in lower reaches of the Columbia (Taylor 1990).

These patterns generally coincide with different adult spawning runs: ocean-type life histories today are most often associated with fall spawning runs in lower reaches, and stream-type are common among spring and summer run adults in the upper basin. The ISG (2000) clearly demonstrates that this presumed dichotomy of juvenile migrant types based on adult run timing is an oversimplification that ignores upriver habitat losses and associated ocean-type life histories, which were likely prevalent among some spring and summer spawning populations. Nonetheless, the general principle of a geographic structure of life histories associated with particular habitat features clearly applies to salmon populations in the Columbia River Basin.

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Salmon Resilience and Production

The geographic structure of salmon populations and the diversity of life histories within and among populations have been described as a strategy that spreads risks and avoids brood failure (Healey 1991). Because not all individuals behave in the same manner or use the same habitats at the same time, life-history diversity affords resilience to salmon in uncertain environments. The use of different spawning and rearing areas maximizes the possibility that any year class will contribute to future generations and maximizes the total production of juveniles from a river system (Carl and Healey 1984).

The importance of life-history diversity is illustrated by the effects of various ocean disturbances on populations that leave estuaries at different times or rear in different ocean areas. Although the population-specific patterns of ocean migration are poorly understood, gross differences among geographically distinct groups of populations ("stocks") may affect the capacity of salmon to withstand strong El Niño events or interdecadal shifts in ocean regimes (e.g., Mantua et al. 1997). For example, tule fall chinook stocks, which spawn in the lower Columbia-Bonneville pool area, migrate primarily off Washington and southern British Columbia, whereas upriver brights from the area between McNary and Preist Rapids Dams rear far north off northern British Columbia and southeastern Alaska (Van Hyning 1973, Beaty 1992). Coastal chinook stocks south of Cape Blanco rear off southern Oregon and northern California, while stocks to the north of Cape Blanco migrate northward (Nicholas and Hankin 1988).

Differences in ocean rearing areas may explain different responses to the strong 1982-83 El Niño event: chinook stocks off southern Oregon and locally distributed stocks from the lower Columbia River suffered high mortality and low returns, whereas northward migrating populations from the Columbia River showed little or no decline in abundance (Johnson 1988).

Differences in the timing of migration of salmon from the estuary to the ocean may also affect the capacity of salmon to adapt to variable ocean conditions. For example, while coho salmon production has been positively associated with periods of strong coastal upwelling in the spring (Nickelson 1986), the timing, strength, and duration of upwelling events is episodic and variable along the coast. Moreover, the seasonal shift from winter conditions to a spring/summer upwelling regime, characterized by changes in winds, coastal currents, temperatures, and density gradients, occurs suddenly at different times each year (Huyer 1983, Strub et al. 1987).

A single upwelling event of a few days' duration in the spring may be sufficient to cause the shift to a spring/summer regime (Huyer 1983). Thus, different times of ocean migration may be advantageous in different years depending, for example, on the onset of the spring/summer transition, the timing and location of upwelling events, the distribution of the Columbia River plume, or the northward extent of warming caused by occasional strong El Niño Southern Oscillation events in the tropics (ISG 2000).

Spence (1995) concluded that variability in ocean entrance by coho salmon has evolved in response to characteristic degrees of ocean variability in different regions of the North Pacific. Comparing 50 smolt populations from California to Kodiak Island, Alaska, he described latitudinal patterns in the timing, duration, and variability of migration. Although migration times varied locally, results suggested that this variability exists within certain temporal "windows of opportunity" among different regions of the North Pacific. Spence further concluded that a more protracted period of migration among coho salmon populations south of the Queen Charlotte Islands (54°N) is likely an adaptive response to increased ocean variability and uncertainty relative to more northern areas.

Diversity of salmon life histories not only minimizes risk in uncertain environments, it is fundamental to salmon productivity. As conditions in freshwater, estuarine, and marine environments vary between years, so may the number of alternative behaviors that will permit life-cycle closure. In relatively favorable conditions, a greater number of life-history types and populations may be "captured," producing a stronger year class for the species as a whole (Fig. 2.2; Bottom et al. 1998). Thus, as proposed by the member-vagrant hypothesis (Sinclair 1988), the absolute abundance of a species may be a function of physically driven expansion and contraction of the spatial (and temporal) extent of areas where life cycle closure is possible.

Life-history diversity thus may affect the overall "carrying capacity" of an estuary for salmon. Some studies present evidence of density-dependent estuarine growth of salmon, which in turn, could affect size at ocean entrance and, through size-specific mortality, ocean survival of smolts (Reimers 1973, Reimers et al. 1979, Healey 1982, Nicholas and Downey 1983, Nicholas and Hankin 1988). As illustrated by the varied life-history types in Sixes (Reimers 1973) and Nanaimo Rivers (Carl and Healey 1984), density-dependent effects may be minimized if the contributing populations of each species in a basin have somewhat different times and sizes at entrance, duration of residence, and migratory paths through the estuary. By spreading their rearing patterns through time and space, not all salmon use the same areas and resources at the same time. Variation in life history thus maximizes basin productivity by allowing a continued "turnover" of available estuarine habitat by different groups of fish staged to move through the system at different times (e.g., Myers and Horton 1982).

Salmon Imprinting and Homing

Added support for the member-vagrant hypothesis comes from recent studies of imprinting and homing by salmon. These results suggest that the idea of salmon "navigating" a chain of habitats to complete their life cycles may be literally and not just metaphorically correct. One hypothesis of the mechanism of homing suggests that juvenile salmon imprint on a series of olfactory signatures as they migrate through a
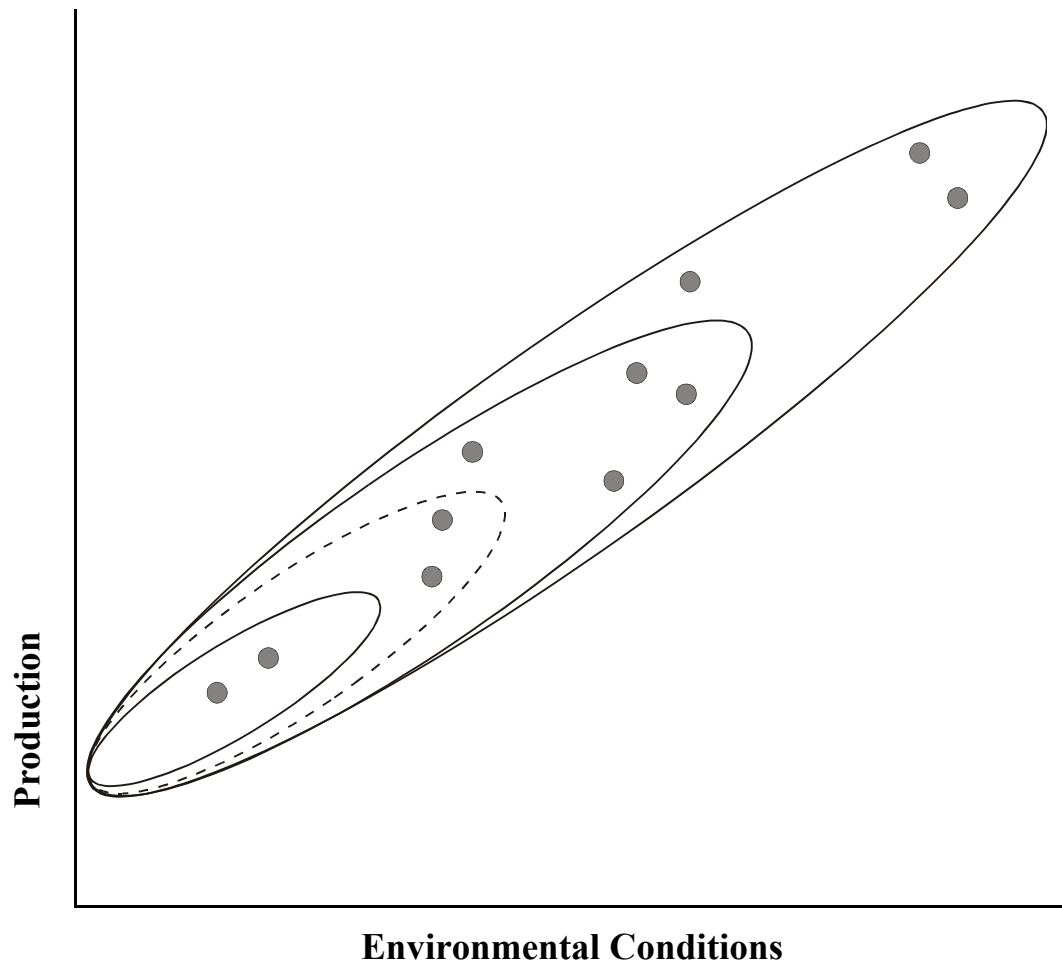
Figure 2.2. Hypothetical salmon production as a function of the number of different salmon life histories (as indicated by the dots) that are "captured" under different environmental conditions. The environments experienced by each life-history type depend on the particular spatial and temporal sequence of habitats used throughout the life cycle of each type (from Bottom et al. 1998).

gradient of habitats to the ocean and retrace this sequence upon returning to their home streams (Harden Jones 1968, Dittman et al. 1996). In experiments to test imprinting of coho salmon at various life stages, Dittman et al. (1996) concluded that simple exposure to odors may not be sufficient but that olfactory stimuli experienced by migrating through a gradient of environmental cues--varying water chemistry, temperatures, lunar cycles, and water velocities, etc.--may be necessary for optimal imprinting. A proposed mechanism for the response to migration is the apparent stimulation of thyroxine production by varying environmental cues, which may facilitate olfactory imprinting (Dittman et al. 1996).

A highly sensitive period for imprinting is the end of the parr-smolt transformation. Dittmann et al. (1996) found little evidence that hatchery salmon imprinted to homing cues before the smolt stage. Fish held for lengthy periods and not allowed to migrate during the parr-smolt transformation were impaired in their homing ability. This suggests that conditions experienced during migration through the tidal-freshwater and estuarine gradient, where salmon gradually adapt to saltwater conditions and reach the end of the smolt stage, may be particularly important to successful imprinting. Interestingly, although wild fish show a capacity to imprint at early ages before the smolt stage, hatchery presmolts in these experiments did not, which may have been due to the stable environment and lack of migration associated with hatchery rearing (Dittman et al. 1996).

Geographic Mechanisms of Population Control

In addition to mortalities associated with competition, predation, and disease, the member-vagrant hypothesis underscores the importance of geographic processes of population control for species that migrate among spatially distant habitats. Even biological interactions at a local scale may be controlled by physical processes that determine, for example, the temporal and spatial availability of salmon habitat or the particular suite of species that salmon encounter when they enter the ocean. Patterns of salmon abundance and habitat use in an estuary are also directly linked to various processes upriver that determine the size, migration timing, and physiological state of downstream migrants. Mechanisms of population control implied by the member-vagrant hypothesis that may be particularly relevant for understanding salmon in estuaries are described below and depicted in Figure 2.3.

Habitat Availability and Connectivity--If salmon migration and rearing behaviors are tied to specific geographic features, then population members may be lost if these features are changed or eliminated by natural or human causes (Fig. 2.3b, Type I). For example, scale analyses comparing past and contemporary life-histories among Rogue River chinook salmon suggest that a former estuarine-rearing life history may have been eliminated, possibly through modifications of the tiny estuary during construction of the jetties and boat basin (Schlucter and Lichatowich 1976). A recent

(a)

LH Type I

LH Type II

LH Type III

(b)

LH Type I

LH Type II

Hatchery

LH Type III

Habitat Loss

Displacement of Fish
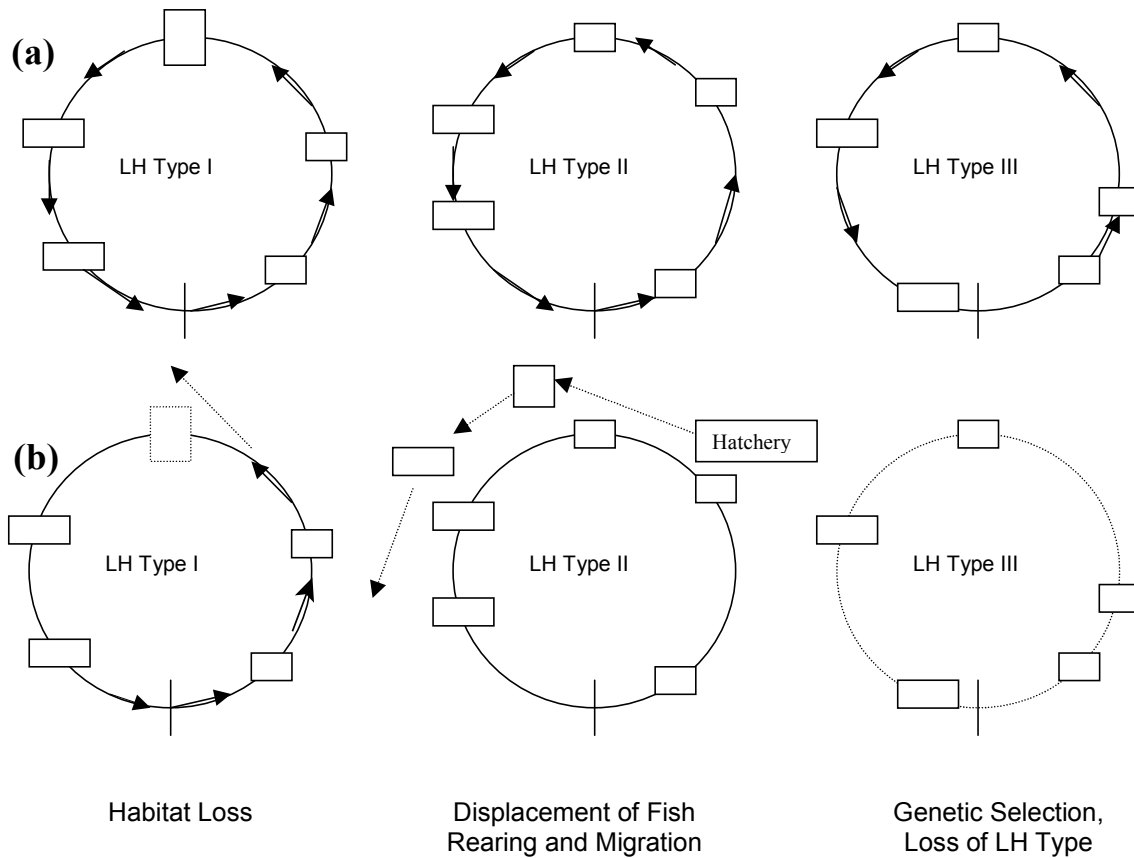Rearing and Migration

Genetic Selection,
Loss of LH Type

Figure 2.3. Three hypothetical salmon life-history types based on different temporal and
spatial patterns of migration and habitat use **(a)**. Boxes depict chains of
rearing habitats along the time/space migration path necessary for life-cycle
closure. Three scenarios of spatial losses affecting life-cycle closure are
shown in **(b)**, depicted by dotted lines: Loss of habitat necessary to support
rearing by Type-I fish; hatchery or transport effects displacing Type-II fish
from the appropriate migration sequence (time, space, and developmental
stage) necessary for optimal imprinting and homing; and intensive selection
pressures that alter spawning and emergence patterns and eliminate Type-III
fish.

review of the five life-history types described in Sixes River (Reimers 1973) raised similar questions about whether warming of the mainstem river may have eliminated an early-large migrant pattern, which is found in some other coastal estuaries (Bottom et al. 1998). Extensive loss of historic estuarine wetlands through widespread diking and filling in Northwest estuaries could reduce or eliminate some subyearling migrant life histories that have been linked to the availability of shallow marsh habitats (e.g., Levy and Northcote 1981, 1982).

If salmon life cycles require specific sequences of habitat in time and space, then areas otherwise capable of supporting salmon may remain unoccupied when their connection to other habitats is lost (Bottom et al. 1998). Thus, habitat conditions and associated subpopulations upriver may ultimately limit the array of life histories expressed in the estuary. Certain estuarine habitats might not be fully occupied, for example, if upstream habitats lost to dam construction, pollution, or other factors supported populations with distinct estuarine rearing behaviors.

One example noted above is the loss of some ocean-type life histories among chinook salmon populations in the Columbia River (ISG 2000). Temperature variations affecting growth opportunity and time of smolting in different areas of the basin may be an important factor determining the geography of chinook life histories (Taylor 1990). Dam construction together with temperature increases in the mainstem and lower subbasins have diminished habitat opportunity upriver and substantially reduced the proportion of ocean-type migrants that are now produced in the Columbia (ISG 2000).

Loss of subyearling migrant types from summer and spring spawners has likely occurred in many areas that historically offered optimal growth opportunity, particularly the warmer middle portions of Columbia sub-basins (Lichatowich and Mobrand 1995, ISG 2000). Because subyearling migrants typically reside in the estuary for longer periods and use different habitats than those with yearling life histories, such losses could have an important influence on contemporary patterns of estuarine rearing by chinook salmon and could leave vacant various shallow-water habitats favored by smaller ocean-type juveniles.

Disturbance Processes--Changes in disturbance processes that displace salmon from the appropriate time and area needed to complete their life cycles or that reduce availability of critical habitats may contribute to population losses. It is likely that Columbia River salmon diversified their migration and rearing behaviors to fully use the wide array of tributary habitats and flow conditions historically represented in the Columbia River Basin.

Because populations varied widely in their migration timing and behaviors, they were not equally vulnerable to environmental disturbance. Disturbance conditions most favorable for one life-history type may have been detrimental to another. However, if the relative benefits of various behaviors changed from year to year, the diversity of life histories would be maintained (ISG 2000).

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Regulation of flows in the Columbia River by mainstem dams has dampened natural fluctuations in the system and may have created a mismatch between certain migration behaviors and the flow/habitat conditions that now exist. For example, stabilization of river flows and establishment of a system of slack-water reservoirs may have shifted the "fitness landscape" toward less favorable conditions for salmon with subyearling life histories, whose migration and feeding behaviors depend on flooded shorelines and complex backwater areas maintained by the interaction of the river with riparian and floodplain habitats (ISG 2000). Flow regulation may similarly influence access to habitats in the estuary due to changes in salinity structure, water velocity, and depths.

Displacement of Fish in Time and Space--Artificial manipulations of salmon development (e.g., smolting), release locations, and migration timing may contribute to population losses from a river system by altering the time and space use of estuarine and marine habitats and increasing rates of straying by adults (Fig. 2.3, Type II). The large proportion of hatchery chinook salmon now released in the Columbia Basin (Chapter 1), many of which are held for extended periods and raised to relatively large sizes, could substantially affect size and time-dependent rearing and migration patterns in the estuary.

In studies of the effects of release date and transportation on hatchery chinook salmon from two Columbia River hatcheries, Pascual and Quinn (1995) documented varying effects on homing ability, which they attributed to disruptions in the sequence and timing of imprinting events through artificial manipulations. From these and other studies, they suggest that the sequence of imprinting events is characterized by the time fish experience a particular location and the physiological state of the fish at that time. Thus, manipulations of release date and transportation of fish may disrupt the migration sequence and increase straying through effects of release date on spawning time, effects of holding fish on the sequence of juvenile imprinting, and interference of imprinting through off-station transport of smolts (Table 2.3).

Population losses due to disruption of the migration sequence are shown by experiments in the Columbia River designed to compare survival of hatchery coho salmon released directly into the estuary and various distances offshore (Solazzi et al. 1991). The results showed progressively greater rates of straying to river basins outside the Columbia with transport distance from the hatchery rearing site. The level of homing reported for some Columbia River hatcheries is much lower than has usually been reported for salmonids, indicating significant spatial losses and raising concerns about genetic interchange among populations (Quinn et al. 1991).

Population Structure and Life History--Many life-history variations in salmon populations have been demonstrated experimentally to be under some degree of genetic control, including, for example, age at maturity (Hankin et al. 1993), time of spawning and rate of egg and larval development (Beacham and Murray 1987), growth rate of juveniles, and age of seaward migration (Carl and Healey 1984, Taylor 1990). Strong selection pressures through harvest, hatchery practices, or other factors that alter the

genetic structure of Columbia River populations may thus affect the patterns of migration and rearing through the estuary even if the habitats needed to support each life-history type are available (Fig. 2.3b, Type III).

Changes in the time of spawning (and therefore emergence) in salmon may be critical to match subsequent developmental stages and life histories to various "time windows" in the environment (e.g., Beaty 1992, Spence 1995). For example, Einum and Fleming (2000) demonstrated a causal link between time of breeding (and thus time of hatching and emergence) and the success of offspring in Atlantic salmon (*Salmon salar*). In this case, later emerging juveniles were smaller than early-emerging ones so that reproductive success could also be affected through differential size selection at subsequent life stages.

In Oregon's Salmon River, the spawning time of coho salmon has advanced one to two months, and the duration of spawning activity has decreased since the hatchery began operating in the mid-1970s (Mullen 1978, 1979; Oregon Dep. Fish. Wildlife, unpubl. spawning data, 1996-1999). Although the specific effects on juvenile rearing patterns in the estuary are uncertain, such changes undoubtedly influence the times of emergence and downstream migration. In recent years, early adult returns has meant that few if any coho salmon spawned after late November flood events, which likely reduced survival of eggs already in the gravel. The possibility of a mismatch between present spawning times and the environment of Salmon River is suggested by the lack of successful recruitment from most naturally spawning hatchery fish: each year, about 95% of the fish spawning naturally in Salmon River are adults produced from a new hatchery brood (Jacobs et al. 2000).

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Table 2.3. Possible mechanisms of increased straying of fish through hatchery and transportation manipulations (from Pascual and Quinn 1995).

I. Effects of release date

    A. Affects time of return

        1. Month at return

        2. Age at return

    B. Affects sequence of imprinting by outmigrating fish

        1. Mismatch between the location and developmental state of fish

        2. Mismatch between the location and the time (e.g., environmental conditions)

II. Effects of transportation

    A. Reduced opportunity to imprint

    B. Genetic adaptation to local conditions

**A Framework for Evaluating Estuarine Requirements
of Columbia River Salmon**

Evaluation Principles and Criteria

To summarize, the member-vagrant hypothesis (Sinclair 1988) and the supporting evidence from studies of salmon populations and life histories offer the following principles as an alternative to production thinking (Table 2.1) for interpreting the role of estuaries in salmon life cycles:

- Salmon have evolved complex life cycles that require a chain of habitats in spatially discrete environments (fresh water, estuary, ocean).

- The resilience and productivity of salmon species depend on their diversity of life histories, including variations in the use of estuarine habitats by juveniles.

- The geographic pattern and diversity of salmon life histories reflect the variety of habitat combinations in time and space by which each species can complete its life cycle.

- Estuaries offer one of many alternative rearing opportunities for salmon to achieve life-cycle closure. Salmon with subyearling life histories are among the most dependent on estuaries for juvenile rearing.

- Variability in salmon abundance is a result of losses from the time/area necessary to ensure membership in a population. Such losses may occur throughout all stages of the salmon life cycle and may involve both geographic ("spatial") and biological ("energetics") processes that may be density-dependent or independent.

These principles emphasize the interaction between salmon behavior (life histories) and various habitat features that salmon use to complete each stage of their life cycle and maintain membership in a population. Thus, conservation of population richness requires the protection of the diverse geographic features that salmon use to achieve life-cycle closure (Sinclair 1988).

From an evolutionary perspective, Healey and Prince (1995) similarly describe the diversity of salmon rearing behaviors as the consequence of unique salmon genotypes interacting with available habitat features. From this perspective, different combinations of habitat and genotype result in a variety of phenotypic behaviors by which salmon can successfully complete their development and reproduce. Among these tactics, for example, are varied times and ages of salmon migration, periods of residency in the estuary, and times and sizes of ocean entry, all behaviors that require a particular sequence of habitats to support them.

SARE draft: Conceptual Approach

The total productive capacity of the Columbia River Basin and the resilience of salmon species are thus a function of all combinations of genotype and habitat that allow for the full expression of salmon rearing and migration behaviors, including diverse life histories in the estuary. To maintain the diversity and productivity of salmon, therefore, requires the conservation of populations within their habitats, protecting the full variety of genotype-phenotype combinations (Healey and Prince 1995).

It follows logically from the above principles that the productive capacity of the Columbia River estuary can be affected by any changes that sever the link between salmon behavior and habitat. As proposed in Figure 2.3, such effects may result from any or all of three categories of life-history/habitat change:

1)   removing habitats, altering habitat functions, or changing disturbance processes that salmon require to express the full diversity of potential rearing behaviors;
2)   altering the geographic structure and genetic characteristics of the component populations of each species that converge in the estuary en route to the ocean; or
3)   directly changing the phenotypic behavior of salmon, including displacement of fish from the time/space sequence of habitats they need to complete their life cycles in their home streams, whether or not the underlying genetic structure of populations is affected.

Based on these categories of change, we patterned our analyses of estuarine rearing conditions (see Chapters 3-5 of this report) on the following attributes:

•   Habitat opportunity--the availability of estuarine habitat for salmon, often determined by physical ("spatial") processes;

•   Habitat capacity--the quality of estuarine habitat for salmon, determined by biological interactions and bioenergetic conditions ("energetics processes");

•   Population structure/life history--phenotypic and genotypic effects at other life stages that are linked to salmon behaviors in the estuary;

•   Performance--the ultimate outcome for salmon within the estuary, as measured by growth, life-history diversity, and foraging success.

Our definition of each attribute and its application to this assessment are discussed below.

Habitat Opportunity--Opportunity involves the capability of juvenile salmon to access and benefit from occupying a habitat. We define this capability broadly based on physical factors, physiological constraints, and ecological interactions (Sanfriel and Ben-Eliahu 1991, Simenstad et al. 2000). These factors involve spatial processes that are largely unaffected by fish density:

Physical:	tidal flooding
	depth
	duration
	frequency
	fluvial flooding
	depth
	duration
	and timing;
	distributary and tidal channel structure
Physiological/Behavioral:	water velocity
	turbidity
Water characteristics and quality:	temperature, salinity, dissolved oxygen, turbidity toxicants
Ecological	proximity to disturbance
	(e.g., noise, movement, etc.)
	refugia from predation
	(e.g., extent of overhanging vegetation, marsh vegetation height, proximity to deepwater habitats)

We distinguish opportunity to occupy habitat from the probability of doing so. Probability involves many other external factors that affect whether juvenile salmon access habitat, for example, variability in salmon populations and life histories that dictate run timing and fish size, density-dependent interactions, the presence and practices of salmon hatcheries, etc. Thus, whether or not a habitat is occupied at a particular time does not affect opportunity.

For the purpose of this evaluation, we first describe historical patterns of environmental disturbance processes in the basin, particularly flow and sediment transport, which may determine variability in estuarine habitat opportunity (Chapter 3). Following this basin-wide assessment, we apply a hydrodynamic modeling approach (Chapter 4) using depth and velocity as principal indicators of habitat opportunity for subyearling chinook salmon (see section below on "Subyearling Chinook Salmon as an Indicator of Estuarine Conditions").

These criteria were chosen because (1) they are important physical features to which juvenile salmon respond, (2) they can be simulated with some accuracy by modeling (as compared to water characteristics or quality), and (3) they are useful descriptors of the major physical changes that have affected conditions in the estuary. Juvenile salmonids, especially those with ocean-type life histories (e.g., fall chinook, chum), tend to select habitat depths based on size: fry (30-50 mm FL) often prefer shallow water less than 1 m deep, fingerlings (50-100 mm FL) are more likely to be found in water deeper than 1 m, and smolts (e.g., >100 mm FL) may be found over any depth. A similar size-related response to water velocities likely occurs because

maintenance (routine) swimming speed increases with fish length, depending upon temperature and other factors (fish condition, dissolved oxygen).

Habitat Capacity--We define capacity to support juvenile salmon as those *qualities* of the habitat that promote juvenile salmon production, including conditions necessary for feeding, growth, growth efficiency, and/or eluding predators (Chapter 5). Capacity thus encompasses what Sinclair (1988) terms "energetics processes," including biological interactions and bioenergic relationships:

• Productivity of selected invertebrate prey, including both quantity and availability

• Physicochemical and ecological conditions that maintain prey production

• salinities and temperatures that promote high assimilation efficiencies

• predation levels as affected by habitat structure and relative vulnerability of salmon (e.g., refugia in vegetation or shallow water) as well as the habitat attributes of predators

Obviously, capacity is time-dependent because prey production can be punctuated, and predation intensity may vary with alternative prey availability, food demands, etc. Many variables interact to affect capacity. For example, turbidity may reduce the feeding efficiency and growth potential of salmon in a particular habitat and, at the same time, reduce their vulnerability to predators. In contrast to the physical factors that regulate habitat opportunity, the variables affecting habitat capacity are often density-dependent. For example, salmon abundance may affect food consumption rates as well as predation levels.

Life History/Population Structure--Whether or not salmon fully realize the opportunity and capacity of estuarine habitats may depend in large measure on factors at other life stages that affect fish behaviors and their patterns of estuarine use. Such effects may be entirely phenotypic, for example, changes in fish size and times of migration associated with hatchery release schedules; transportation of fish around dams; or changing temperatures or flow regimes. On the other hand, selection pressures from hatcheries, harvest, or elimination of upriver habitat may also alter the genetic and geographic structure of upriver populations and thereby eliminate certain rearing behaviors. Changing release dates from hatcheries, for example, may alter time and age of return, with subsequent effects on emergence times and downstream patterns of estuarine use. Loss or substantial decline of upriver populations through overharvest of wild stocks or loss of spawning habitats may eliminate various combinations of genotype-habitat interaction that are responsible for unique life-history patterns downstream. Although the focus of our evaluation is clearly the estuary, our conceptual approach dictates that we must also be aware of genetic or behavioral factors at other life stages that can influence the estuarine performance of juvenile salmon.

Performance--The ultimate measure of performance for Columbia Basin salmonids is the diversity of self-sustaining populations within their natal habitats, which is reflected in the overall resilience and productivity of each species from the basin as a whole. For the purpose of this evaluation, we define performance more narrowly based on the diversity of physiological and behavioral patterns of subyearling chinook within the estuary. We assume that the diversity of habitat-specific residence times, range in migration timing, growth, and foraging success in the estuary are all indicators of the relative capacity of the estuary to accommodate chinook and all its component populations and life-history types (see Chapter 6).

Our conceptual approach further suggests that optimal performance in the estuary as defined by these indicators will also favor salmon diversity and productivity in the basin as a whole. We interpret salmonid performance and the effects of flow regulation in light of our results for all three factors described above: opportunity, capacity, and life history/population structure.

Subyearling Chinook Salmon as an Indicator of Estuarine Conditions

The patterns of habitat use within the Columbia River estuary vary among salmon species and life-history types within species. Figure 2.4 is a generalized model of the alternate paths of rearing and migration that different salmon species may use to complete their life cycles in the Columbia River. Of these, juvenile pink salmon, sockeye salmon, or steelhead trout likely spend the least amount of time in the estuary. Various life-history types of chinook and most chum salmon may remain for longer periods, where they actively feed and grow before ocean entrance (Healey 1982, Thorpe 1994). Although coho salmon may use estuarine habitats for significant periods, particularly in the tidal freshwater zone, and there is increasing evidence that subyearling migrants in some estuaries grow rapidly enough to migrate to sea in their first year of life, we have insufficient data to verify estuarine life histories of coho in the Columbia River.

Two major types of life history are commonly distinguished among chinook salmon: "stream-type" juveniles that rear in fresh water for at least a year before migrating directly to sea, and "ocean-type" juveniles that spend variable amounts of time in the river and estuary before migrating seaward as subyearlings. For this evaluation, we emphasize subyearling chinook salmon because they have the longest period of estuarine residency among salmonids, and past surveys provide at least some information to interpret variations in their rearing behavior. Results for chinook may also apply to other species with subyearling migrants, particularly chum salmon.

The continuous influx of individuals to the estuary from diverse tributaries noted by Rich (1920) raises the possibility that subyearling chinook salmon may exhibit a broader continuum of estuarine rearing and migratory tactics in the Columbia Basin than has been presumed from relatively few estuarine studies. Looking just at 11 tributaries within the lower Columbia River, Reimers and Loeffel (1967) found that juveniles from various streams either migrated immediately after emergence or remained in fresh water
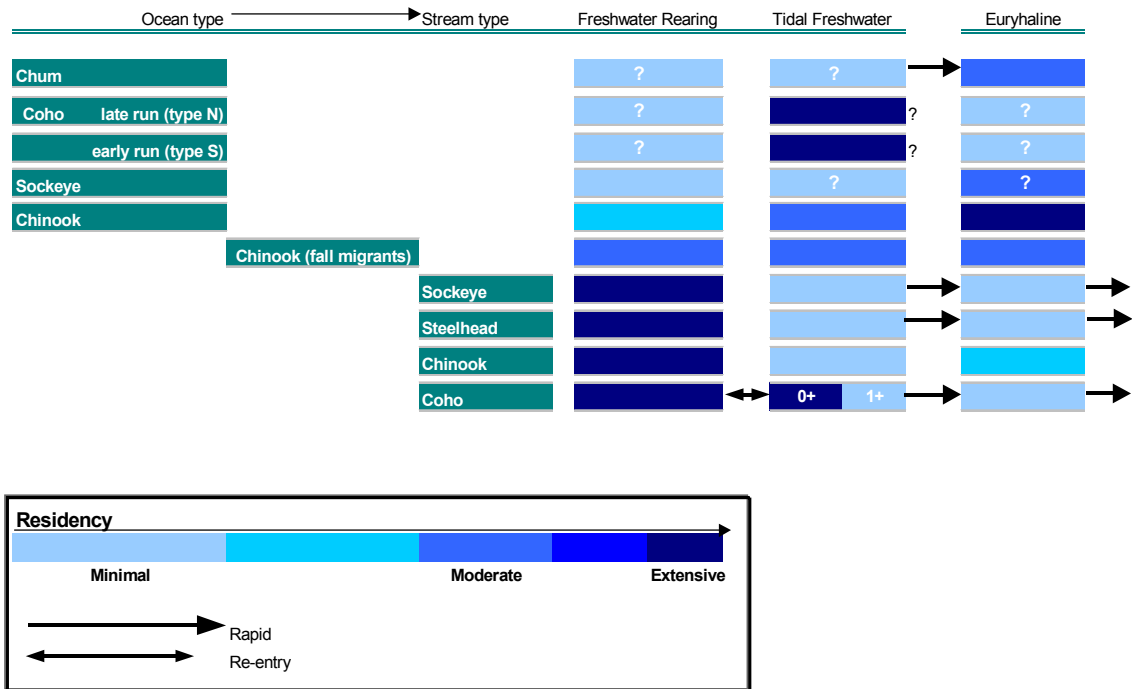
Figure 2.4. Proposed model of relative migration rates and residence times for salmonid species in freshwater and estuarine rearing environments of the Columbia River Basin.

for as long as 5 months. Rich (1920) found that some individuals enter the estuary very soon after emergence where they may remain for up to several months before migrating to the ocean (Rich 1920), a pattern that has been observed in some small estuaries (Reimers 1973, Carl and Healey 1984). Duration of freshwater residence among populations scattered widely throughout the Columbia River Basin may be affected by the migration distance downstream. As part of our analysis in Chapter 6, we re-assess diversity of subyearling rearing behaviors from the results of previous salmon inventories in the Columbia River estuary.

3. CHANGES IN HYDROLOGICAL CONDITIONS

Introduction

Columbia River mainstem flow and sediment transport affect salmonids in numerous ways (Weitkamp 1994, Chapter 1). Salmonids respond directly to hydrographical factors (temperature, salinity, turbidity) controlled or influenced by river flow and to current velocities set in part by river flow. Habitat availability is a function of river stage as well as human alterations to the system. Major disturbances such as large floods may create, destroy or alter salmonid habitats. Finally, water column turbidity may affect food supply for, feeding by, and predation on juvenile salmonids.

The multiple aspects of salmonid dependence on hydrological properties mean that it is vital to document changes in Columbia River hydrological processes over historic time. Especially important to downstream migrant salmonids are changes in the magnitude and timing of the spring freshet. Intelligent formulation of future management options also requires that human and climate-induced impacts on the historical record be separated as cleanly as possible.

Distinguishing between climate and human impacts on Columbia River flow and sediment transport poses two primary difficulties: one procedural and one conceptual. The procedural problem is the paucity of records that may be used to infer cause and effect, a problem that affects most of the analyses in this review. The conceptual problem is that the non-linearity of ecosystem processes often renders the partitioning of responsibility for a given change between human intervention and climate fluctuations imprecise. However, reasonably solid conclusions can still be reached when one effect is dominant.

This chapter examines the effects of anthropogenic and climate-induced changes in Columbia River hydrological processes over the last 140 years. The general hydrological characteristics of the system are described first. This is followed by descriptions of sub-basin characteristics, data sources, and the regional climatological background. Human and climate effects on the specific hydrological processes relevant to salmonids are then described. These processes include magnitude and timing of river flow, fine and coarse sediment input, frequency of extreme events and overbank flow, occurrence of freshet styles, and changes in sub-basin flow characteristics.

The analyses described below show that direct human manipulation of river flow (through flood control, water withdrawal, and hydropower generation) have been responsible for the largest hydrological changes in the system. Still, climate change, climate fluctuation, and channel development such as navigational dredging, diking and filling, and land use are individually important and interact with river flow manipulation. Thus, channel development is likely the primary factor affecting estuarine salinity intrusion, but reduced freshet flows have also increased salinity intrusion during the spring season.

Also, flow regulation and diking have combined to drastically reduce overbank flow. The hydrological factors discussed here affect not only the river, but the estuary and coastal ocean as well. Moving in a seaward direction, the effects of hydrological alterations on the river are well-defined, those on the estuary reasonably clear, and those on the coastal ocean uncertain and largely beyond the scope of this review.

General Hydrological Characteristics

The Columbia River has the largest average flow (~7,300 m^3s^{-1}) of any river on the Pacific coast of North America, although its sediment discharge (~10^7 metric tons (t) year^{-1}) is exceeded by that of the Eel River in California and by that of the Fraser River in British Columbia (Church and McLean 1992, Jay and Naik 2000). The Columbia River contributes some 60% (winter) to 90% (summer) of the total freshwater input between San Francisco and the Strait of Juan de Fuca and strongly affects regional seawater properties of the Northeast Pacific Ocean (Barnes et al. 1972).

The Cascade Mountain range of Oregon and Washington divides the Columbia River drainage basin into interior and western sub-basins. The moist and relatively warm western sub-basin contains only ~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 sub-basin is at too low an elevation to accumulate a large seasonal snow pack. Thus, the highest flows are observed during and shortly after winter storms, between December and March. In contrast, most of the flow in the interior sub-basin occurs as the result of melting of a seasonal snow pack between April and June. Much of the interior sub-basin is relatively arid, but its Canadian component experiences heavy winter snowfall and plays a major role in spring freshet flows.

Columbia River flows and sediment loads have been altered by water withdrawal for irrigation and by construction of 28 large and numerous small dams (Simenstad et al. 1992). Water withdrawal was minimal before 1890, but this increased rapidly between 1890 and 1920, and again after 1960. Dams were constructed to generate power, control floods, and to facilitate irrigation. The first two dams with more than 10^6 m^3 of active storage were built on the Snake River (Jackson Lake, 1916 and American Falls, 1926). The first major mainstem dams completed were Bonneville (1937, with only a modest storage capacity) and Grand Coulee (1938) Dams. Completion of seven large dams high in the basin between 1967 and 1973 more than doubled the storage capacity of the total dam system to 70 x 10^6 m^3 and provided a considerable increase in storage retention time.

These factors, together with an integrated approach to management of the system, suggest the 1969-1970 period as the boundary between the "early" and "modern" periods of hydrological management of the system, a division we employed in data analyses. Our analyses suggested that the 19th century also had distinctive climate patterns;

however, flow regulation was insignificant and diversions were small, at least until the 1890s (Simons 1953).

A regional perspective on the climatological setting and modifications to the Columbia is also useful. There is a continental-scale, north-to-south decrease in base river flow due to glacial melt and annual snow cover. Because more northerly rivers have a stable base flow, seasonal flow fluctuations and interannual variability increase southward from the Fraser to the Columbia interior sub-basin, to the Willamette River, and to California rivers such as the Sacramento and San Joaquin (Milliman 1980, Berg et al. 1991, Cayan et al. 1993).

Flow regulation and water withdrawal also increase from north to south: diversion of water from the Fraser is only a small percentage, while that from tributaries to San Francisco Bay is about 50% (McLean and Church 1986, Rozengurt et al. 1987). The Columbia occupies an intermediate position in this regard as well. As discussed below, the Columbia's dependence on mean flow level for flow variability and sediment transport is, however, higher than that for other major West Coast rivers (Naik and Jay in prep. a). Because sediment transport is so strongly related to maximum flows, the sediment transport regime in the Columbia is more sensitive to alterations of the annual flow cycle than is the case for other major West Coast rivers.

Data Sources used for Hydrological Analyses

The Columbia River daily flow record compiled by the U.S. Geological Survey (USGS) for The Dalles, Oregon (1878-present) is the longest for any Pacific coast river. Annual maximum flow is available from 1858 (Henshaw and Dean 1915), but the dates of the maximum flows were not noted until the daily record was initiated. USGS daily river flow records for the Willamette River at Albany, Oregon, were also initiated in 1878, but are fragmentary until 1892; the Albany gauge includes about 63% of the total flow of the Willamette River. Finally, there is a USGS record for the Spokane River at Spokane, Washington, beginning in 1891. Daily flow records for the oldest Canadian gauging station (Nicholson, B.C., compiled by Environment Canada) began in 1903, while USGS daily records for the Snake River (Ice Harbor, Washington) began in 1912.

It is important also to have an estimate of total flow from the interior and western sub-basins together, determined as close to the mouth as possible. Flows at Beaver, Oregon, (River Kilometer 85) have been measured by USGS only from 1969 to1970 and from 1991 to present. We have used regression analysis of daily records for Beaver, Albany, and The Dalles to hindcast a Beaver daily flow for the common period of record for Albany and The Dalles. This record is complete for 1892-present, and partial for 1878-1892. USGS sediment transport records for the mainstem are available for 1963-1970 (Vancouver, Washington or Beaver, Oregon; Haushild et al. 1966, Hubbell et al. 1971, USGS 1999). USGS sediment transport data for the Willamette are available for 1910-1913 (incomplete; Van Winkle 1914a,b) and 1962-1963 (Haushild et al. 1966).

All hydrological data discussed below are compiled by water year; the water year begins October 1 and ends September 30. Flows have typically been rounded to 10 m^3s^{-1} and sediment transports to two or three significant digits. Formal confidence limits have not been given in most cases because systematic biases may outweigh random errors.

Hydrological Effects of Climate Cycles

Climate-induced variations in Columbia River flow occur on time scales from a few years to centuries (Chatters and Hoover 1986, 1992), and these fluctuations are important to salmonid survival. There is, for example, a correlation between indices of the Pacific Decadal Oscillation (PDO, typically 40-50 years in duration) and salmon catches since 1900 in both the Pacific Northwest and the Bering Sea (Mantua et al. 1997). The cold phase of the PDO (e.g., the 1945-1976 period) was generally favorable for salmonid production in the Pacific Northwest and unfavorable in the Bering Sea. The opposite circumstance prevails during the warm phase, for example, from 1977 to about 1995. Another cold, wet phase seems to have commenced about 1996, and we define the climatic "present" in terms of PDO cycles as the 1945-1999 period.

These PDO-related fluctuations in salmonid survival have been linked to the degree of density stratification of the coastal ocean (Gargett 1997), but are also likely influenced by conditions within the river and estuary (e.g., salinity, turbidity, and river flow itself). Indices of the El Niño-Southern Oscillation (ENSO; typically 3-7 years in duration) are correlated with Columbia River flow and sediment transport (Redmond and Koch 1991). ENSO cycles may also affect upwelling and primary production and therefore survival of salmonids in coastal waters. Because strong El Niño or La Niña events typically last only one to two years, definition of ENSO impacts on salmonids is less clear-cut than is the case with PDO impacts.

The Columbia Basin's climate response is conditioned by its position between 41º30' and 54º40'N lat., within a latitudinal band of strong response to the ENSO cycle and to the PDO (Mantua et al. 1997). While the flow per unit area is much larger in the western than in the interior sub-basin, 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 sub-basin. Below we explore important estuarine and fluvial impacts of these climate cycles that may also affect survival of salmonids.

There are significant uncertainties in inferring 19th-century climate conditions because standard hydrological time series are scarce or absent. The status of the PDO before 1890 remains uncertain, for example, though the fluctuations described by the PDO index have been occurring for at least 300 years and perhaps for thousands of years (Finney et al. 2000). However, it is difficult to find any evidence in the Columbia River flow data that a warm-PDO phase occurred any time between about 1849 and 1900. If

the entire 1849-1920 period is considered to be a cold-PDO phase, then it was much more persistent than has been the case for cold-PDO phases during the 20th century.

The results of Finney et al. (2000) may also suggest that conditions in the latter part of the 19th century were simultaneously favorable for salmonids in both the Columbia and in Alaska, a situation which has not occurred since 1900. Alternatively, estimates of Columbia River salmonid stocks before 1900 are confounded by the rapid growth of commercial fisheries and may not be sufficiently accurate to have allowed correlations with climate. We therefore explore correlations between climate and Columbia River hydrological processes with the caveat that climate cycles before 1900 are not well understood.

El Niño Southern Oscillation and Pacific Decadal Oscillation
Effects on Annual Flow Cycle

El Niño winters in the Pacific Northwest often bring high sea level, warm air temperature, low precipitation, low snow-pack, and weak subsequent spring freshet flows (Kathya and Dracup 1993, Draycup and Kathya 1994). La Niña winters 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. Considering PDO cycles alone, average annual Columbia River flows at The Dalles and Willamette River flows, respectively, were 109 and 102% of the long-term average in the 1890-1921 cold phase, 86 and 87% of average in the 1922-1944 warm phase, 102 and 110% of average in the 1945-1976 cold phase, and 88 and 88% of average in the 1977-1995 warm phase.

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). The net effect is that during an El Niño/warm-PDO combination, respective average annual Columbia River flows at The Dalles and Willamette River flows are 85 and 81% of the long-term annual average, while in case of a La Niña/cold-PDO combination, they are 111 and 119%, respectively (Fig. 3.1a). (These differences are significant at the 95% confidence limit.) Conversely, El Niño effects are suppressed during the cold-PDO phase as are those of La Niña during the warm-PDO phase. However, the number of years in these extreme categories is limited.

Sediment Transport: Amplification of Climate Effects

Effects of the above climate cycles on river flow are substantial. Yet climate impacts on salmonids are not just substantial, they are dramatic. This raises an obvious question: where in the river-estuary system are these climate effects amplified? Sediment transport is one obvious point where amplification can occur; ENSO and PDO effects on sediment discharge are much larger than those on streamflow, because
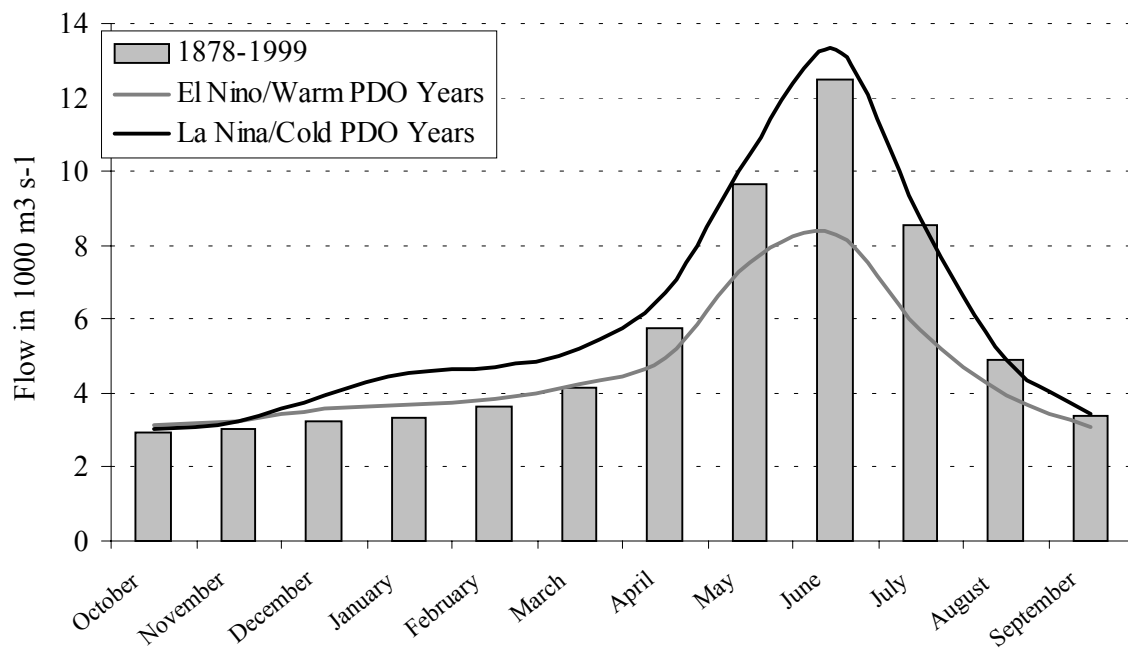
Figure 3.1a. The ENSO/PDO response of interior sub-basin flow at The Dalles.

sediment discharge increases more than linearly with flow. During El Niño years, annual average total sediment transports in the Columbia and the Willamette Rivers are 12.7 x 10^6 and 1.4 x 10^6 t, respectively, while in La Niña years, they are 21 x 10^6 and 2.3 x 10^6 t, or about 65% larger. El Niño years in the warm-PDO phase typically exhibit a very low sediment transport (10 x10^6 t in the Columbia and 1.1 x 10^6 t in the Willamette) while in the La Niña/cold-PDO combination, the transport of suspended particulate matter is more than twice that during the El Niño/ warm-PDO years (23 x 10^6 t for the Columbia and 2.2 x 10^6 t for the Willamette; Fig. 3.1b).

Further amplification of climate effects may take place through estuarine circulation and by the detritally based estuarine food web. That is, the organic matter supplied during the spring freshet that supports estuarine secondary production throughout the summer and fall seasons. However, for this organic matter to be utilized by the estuarine food web including juvenile salmonids, it must first be retained or trapped by estuarine circulation processes active in the estuarine turbidity maximum (ETM).

Analyses of CORIE moored data (Fain et al. in review) suggests that very high river flows result in relatively weak particle trapping, because the high flow decreases the salinity intrusion length over which the particles can be trapped. A moderate river flow level, however, enhances the strength of nearbed upstream bottom flow, enhancing particle trapping without unduly decreasing salinity intrusion. Also, suspended particulate matter is stored in peripheral bays during high flow periods, and subsequently released to the ETM. Thus, the most efficient trapping of particulates is likely to occur during years when there is a strong spring freshet and moderate summer flows to provide a continuous supply of suspended matter. Moderate levels of turbidity, for example during summers after a strong spring freshet, may also promote juvenile salmonid survival by depressing visually based predation.

Sub-Basin Sources of Flow and Major Freshets

Sub-Basin Sources of Flow

Understanding the response of the Columbia Basin to perturbations requires attention to the diverse properties of its sub-basins. There is, for example, wide variability in the percentage of flow from various parts of the basin during the spring freshet and over the water year. The western sub-basin (with ~8% of total area and one-quarter of total flow at the mouth) is obviously very wet. The Canadian part of the interior sub-basin also has a high runoff per unit area. Canada accounts for ~50% of the flow at The Dalles (37% of the flow at the mouth) but has only 25% of the total surface area of the interior sub-basin (19% of the total surface area). The Snake River is relatively dry, with ~40% of the interior sub-basin surface area but only 30% of the flow at The Dalles.
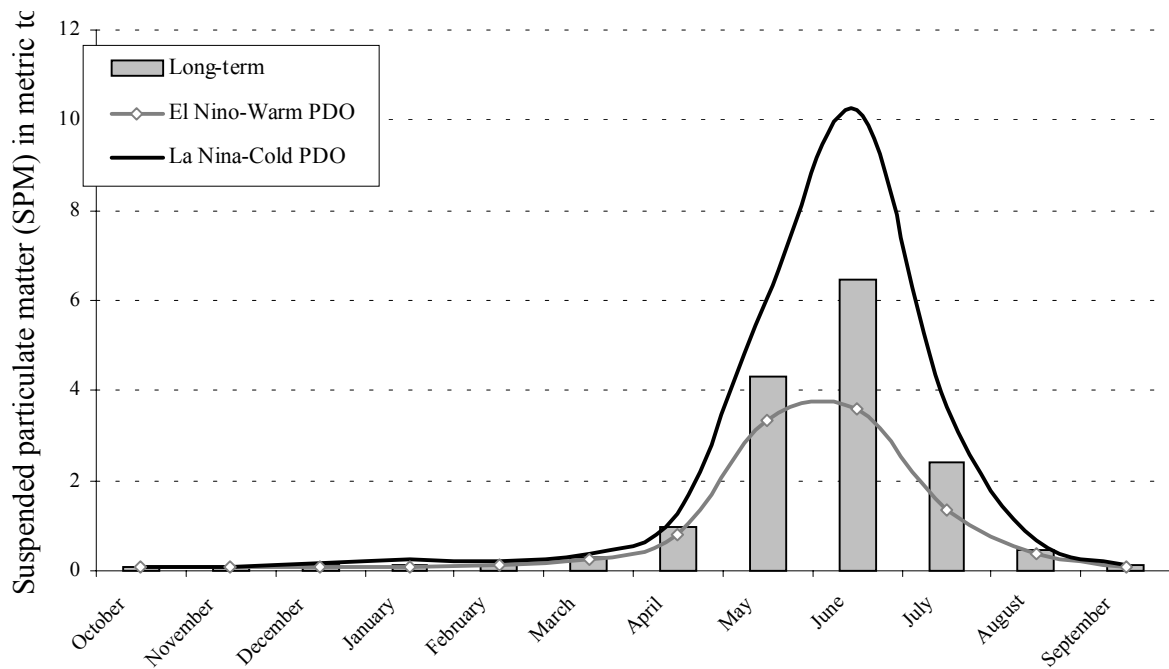
Figure 3.1b. The ENSO/PDO response of interior sub-basin total sediment load/climate effects on flow are amplified in the sediment transport, because of the non-linear dependence of transport on flows.

In very high flow years, half or more of the flow at The Dalles comes out of Canada. During the largest known freshet (1894), for example, the peak flow at Grand Coulee was ~20,500 m^3s^{-1} compared to a maximum flow of 34,800 m^3s^{-1} at The Dalles and ~39,400 m^3s^{-1} at Beaver (estimated). The Canadian contribution to the spring freshet has been declining since 1970 due to the long water-retention time of the dams in Canada. These dams are very effective in changing the seasonality of the flow in the Upper Columbia, which in turn affects flows in the entire main stem.

An important feature of the system's hydrological regime is the fact that the snow-melt occurs earlier in the Snake River area (the most southerly part of the interior sub-basin) than in the upper Columbia. The difference in the timing of maximum flow over the different sub-basins determines freshet length and plays a role in determining the maximum flow level. In years when snowmelt occurs almost simultaneously throughout the Columbia River basin, maximum flows will be higher because the duration of the freshet is shorter.

This can occur when the Snake River sub-basin snow melt is delayed and coincides more closely with that of the upper Columbia. It can also occur when heavy rain accelerates snowmelt throughout the basin, as occurred in 1894 and 1948. When the spring is cold, the late snowmelt in the Canadian part of the basin delays the freshet into July. Because of higher temperatures this pattern is now rarely seen in the Columbia, but it is still sometimes observed in the Fraser River (e.g., in 1999).

Inferences from Selected Flow Histories

Spring freshets are particularly important to the downstream migrations of juvenile salmon. Large freshets also modify habitat structure and distribution and thereby affect future salmon year classes. On the other hand, poor water quality and habitat opportunity may decline during very dry years, effects that are further exacerbated by human alterations. Thus, the flow histories of these extreme years convey important lessons because salmon are most severely tested under stressful climatic conditions.

Very large freshets before modern flow regulation (i.e., before ~1970) lasted 30 to 60 days, with the sharpness of the peak largely governed by the relative timing of snowmelt throughout the basin. Significant winter snowmelt events occur in many winters before a major spring freshet, for example 1894, 1948, 1956, 1974, and 1997; these winter freshets reduce the intensity of the following spring freshet. The occurrence of major freshets even after winter melt events emphasizes the magnitude of the snow pack in such years. Flow regulation decreases spring freshet magnitude and increases flows during the rest of year through winter draw-down of reservoirs, filling of the reservoirs during the freshet, and de-synchronization of flow peaks throughout the basin.

SARE draft: Hydrological Conditions

The result is a "spring" freshet in high-flow years like 1996 and 1997 that lasts from January to June. The effects of human manipulation (especially a weekly power peaking cycle) are extremely prominent during very low flow years like 1977 and 1992. The spring freshet in such years is an almost totally artificial event. The closest pre-regulation analog to such years (1926) still showed a marked annual cycle, though it was of reduced intensity.

The years 1880 and 1916 play an important role in the present study. The model simulations described in Chapter 4 use 1880 as typical of a 19th-century high-flow year. Modeling the system as it was before human alteration required choosing a time period before significant water withdrawal and navigational development. The year 1880 was chosen because a) it was the earliest year for which complete flow records were available at The Dalles and for the Willamette River, and b) navigational development and irrigation withdrawal began soon afterward.

Important parts of the salmonid sampling described by Rich (1920) took place in 1916. Also, 1880 and 1916 are notable for their late freshets, the latest in the 1878-2000 period, when peak flows in both years occurred in early July. In 1880, elevated flows continued until early September, leading to the highest August flows ever observed in the system. At the other extreme is the year 2000. Although the total annual flow volume was not especially low, 2000 stands out for having the earliest recorded freshet peak (23 April) due to flow regulation and a very mild winter.

Human and Climate-Induced Changes to the
River Flow Magnitude and Timing

Total Annual Average River Discharge from the Interior Sub-Basin

Changes in annual average flow are an important integral measure of changes in a river system. In the Columbia, about 97% flow from the interior sub-basin (>70% of the flow at the mouth) passes the gauge at The Dalles, making the long (1878-present) record very useful for understanding changes in this part of the system. Separation of human and climate influences on river flow requires, however, use of three distinct measures of river flow at The Dalles:

Observed flow--The flow observed at a gauge, available on a daily basis for 1878-present (Fig. 3.2).

Estimated adjusted flow--The observed flow corrected for reservoir manipulations calculated by the USGS on a monthly basis for 1878-present as per Orem (1968). We have calculated a daily adjusted flow index for the 1878-1999 period (Fig. 3.3).
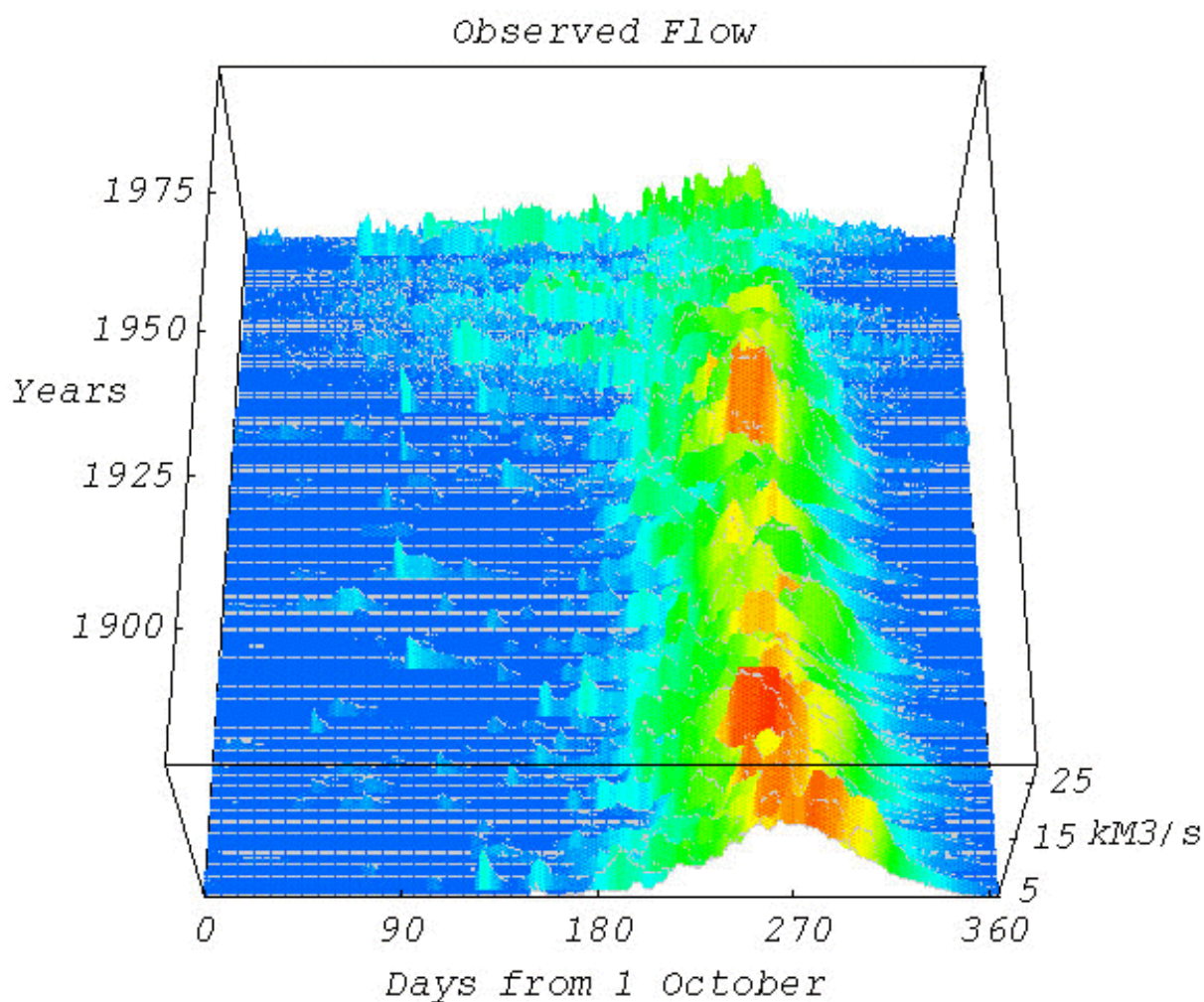
Figure 3.2. Daily observed Columbia River interior sub-basin flow at the Dalles, 1879-1999. Note, in comparison to the virgin flow in Figure 3.4, the enhanced winter flows, reduced spring freshet, and early spring freshet peaks after about 1968. A floor has been set at 4,000 m^3 s^{-1} to emphasize high-flow periods.
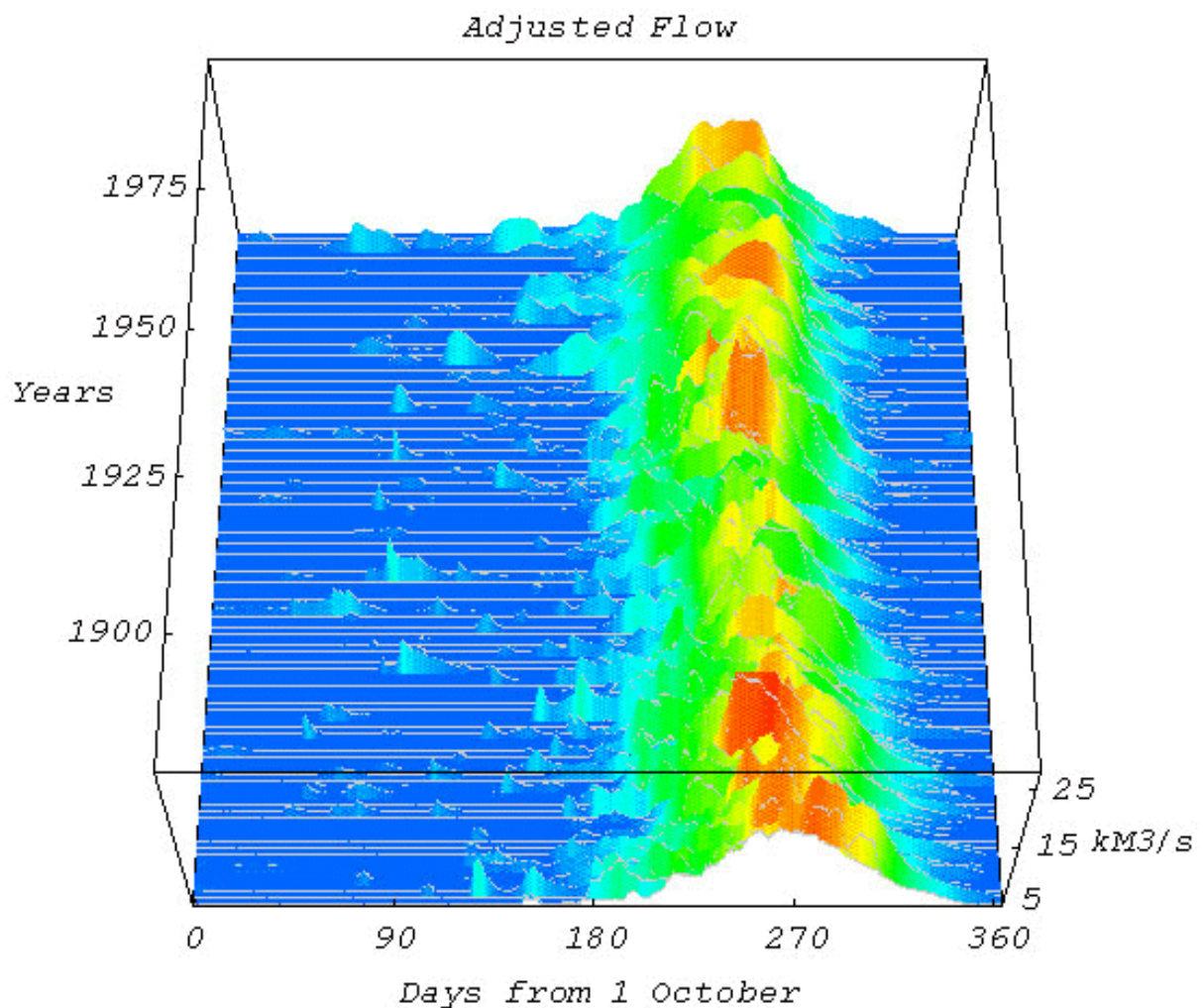
SARE draft: Hydrological Conditions

Figure 3.3. Daily adjusted Columbia River interior sub-basin flow at the Dalles, 1879-1999. The adjusted flow is the observed flow corrected for reservoir manipulations. Note in comparison to the virgin flow in Figure 3.4, the reduced spring freshet and early spring freshet peaks after about 1968. A floor has been set at 4,000 m^3 s^{-1} to emphasize high flow periods.
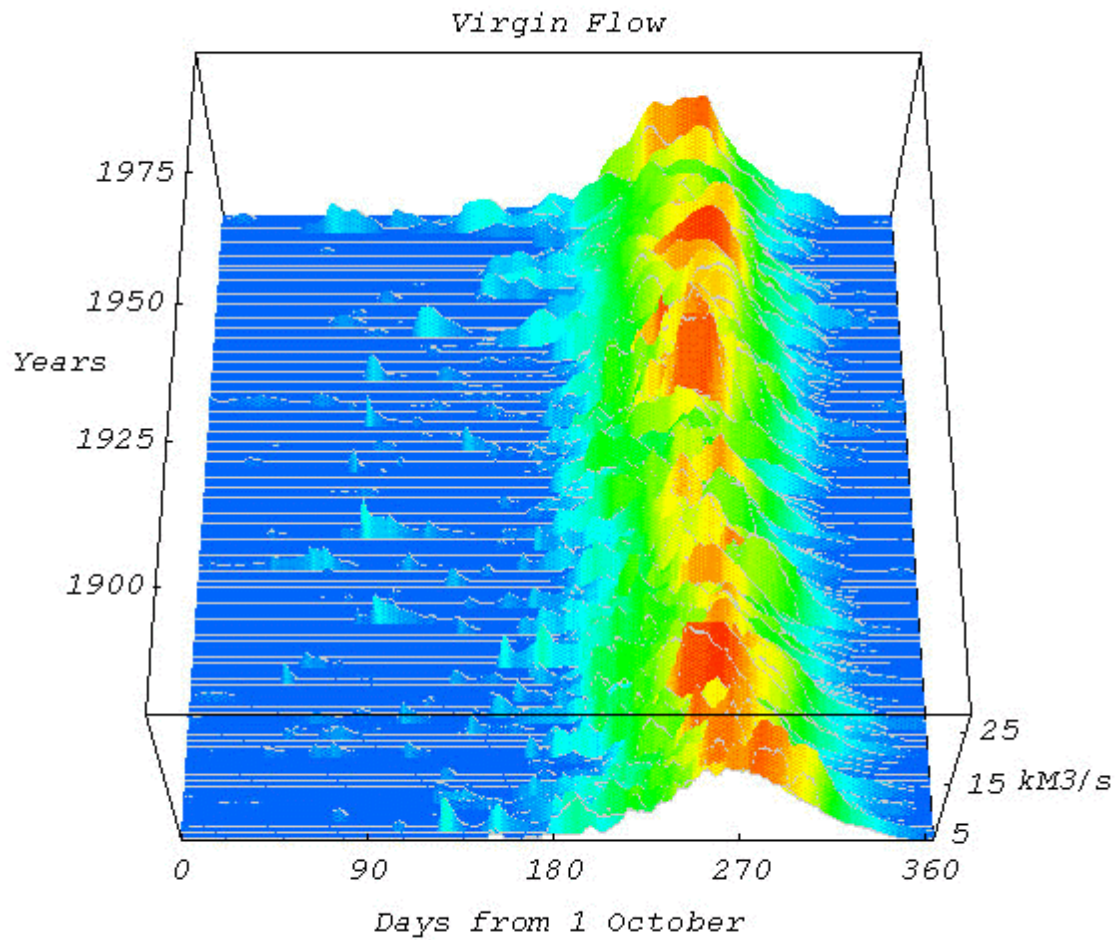
Figure 3.4. Estimated daily virgin Columbia River interior sub-basin flow at The Dalles, 1879-1999. The virgin flow is flow that would have occurred in the absence of human manipulation. Note the low winter flows throughout the record and the late spring freshet in the early part of the record. A floor has been set at 4,000 m^3 s^{-1} to emphasize high flow periods.

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Estimated virgin flow--An estimate of the river flow as it would be without human alteration; i.e., the observed flow corrected by the Bonneville Power Administration (BPA 1993) for reservoir manipulation and irrigation depletion and return flows for the 1929-1989 period. We have completed the virgin flow time series for the 1878-1999 period and calculated a daily virgin flow index (Naik and Jay in prep. b; Fig. 3.4).

Effects of flow regulation and hydropower generation can be judged by comparison of the observed and adjusted flows at The Dalles; the impacts of water withdrawal can be determined from comparison of the adjusted and virgin flows (Fig. 3.5a). Climate effects can be estimated by examining changes in the magnitude and timing of the virgin flow over time (Fig. 3.5b). The total of all climate and anthropogenic effects can be seen by comparison of the virgin flow before 1900 at The Dalles with the observed flow since 1945. There is one significant caution: the flow at The Dalles represents the interior sub-basin only. Virgin and adjusted flow estimates are not available for the Willamette and other west-side rivers, and anthropogenic and climate effects on western sub-basin rivers are not well understood.

It is also difficult to partition the total reduction in flow between human and climate factors, because of the need to both average over climate cycles (specifically the PDO) and to account for changes in flow regulation and irrigation that take place on shorter time scales. As noted above, the "present" averaged over PDO cycles can be defined using the 1945-1999 period. In terms of flow regulation and irrigation, it is useful to define the post-1970 period as the "present."

The mean annual average Columbia River virgin flow at The Dalles has decreased ~7.4% or 470 m^3s^{-1} from 6,320 m^3s^{-1} for 1879-1899 to 5,850 m^3s^{-1} for 1945–1999. This represents the flow decrease due to climate change (Fig. 3.5b). If annual average flow is estimated from the maximum freshet flow each year for the period 1858-1978, then annual average flow for the 1858-1899 period was 6,280 m^3s^{-1}, little different from 1879-1899. Glacial retreat during the last half of the 19th century (following the end of the "Little Ice Age") may have played a role in the observed high 19th-century virgin flow in the Columbia River, but is unlikely to account for most of the difference between the present and the late 19th century. The last half of the 19th century had a rather different (wetter and cooler) climate regime, and very high flows occurred in most years between 1858 and 1900.

The 1945-1999 annual average loss due to water withdrawal for irrigation (difference between virgin flow and flow adjusted for reservoir manipulation) is 440 m^3s^{-1} or ~7% of the 19th-century virgin flow. The 1970-1999 annual average loss due to water withdrawal for irrigation is 470 m^3s^{-1} or ~7.4% of the 19th-century virgin flow.
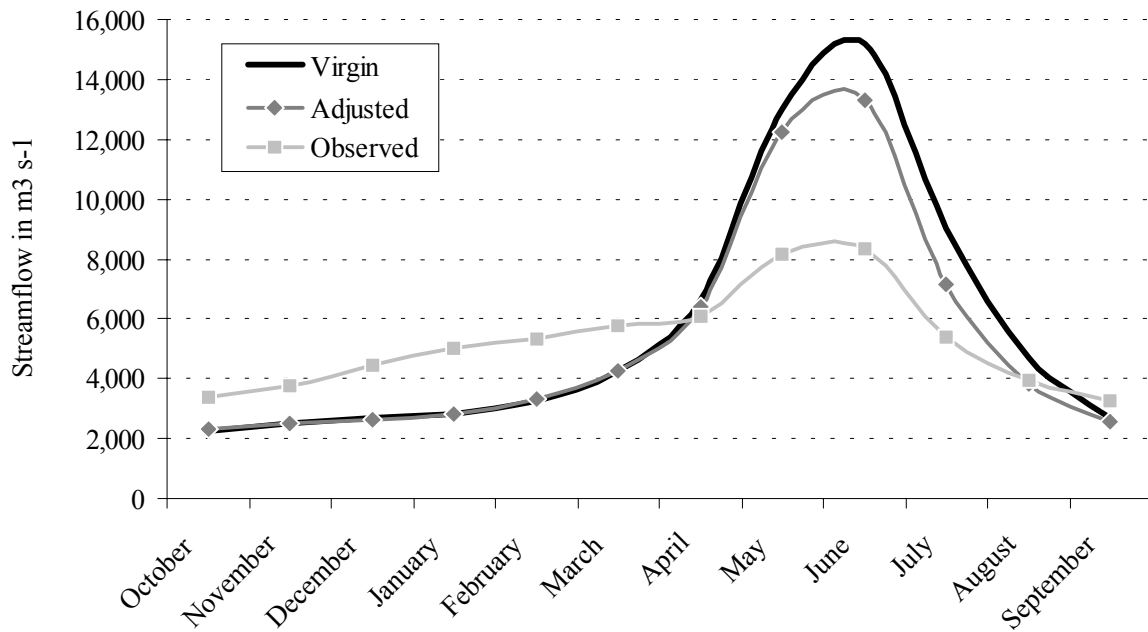
Figure 3.5a. Comparison of the monthly averaged Columbia River interior sub-basin virgin, adjusted, and observed river-flow estimates 1970-1999. Flow regulation and irrigation depletion have greatly decreased spring and summer flows (May to August), while increasing flows from September to March.
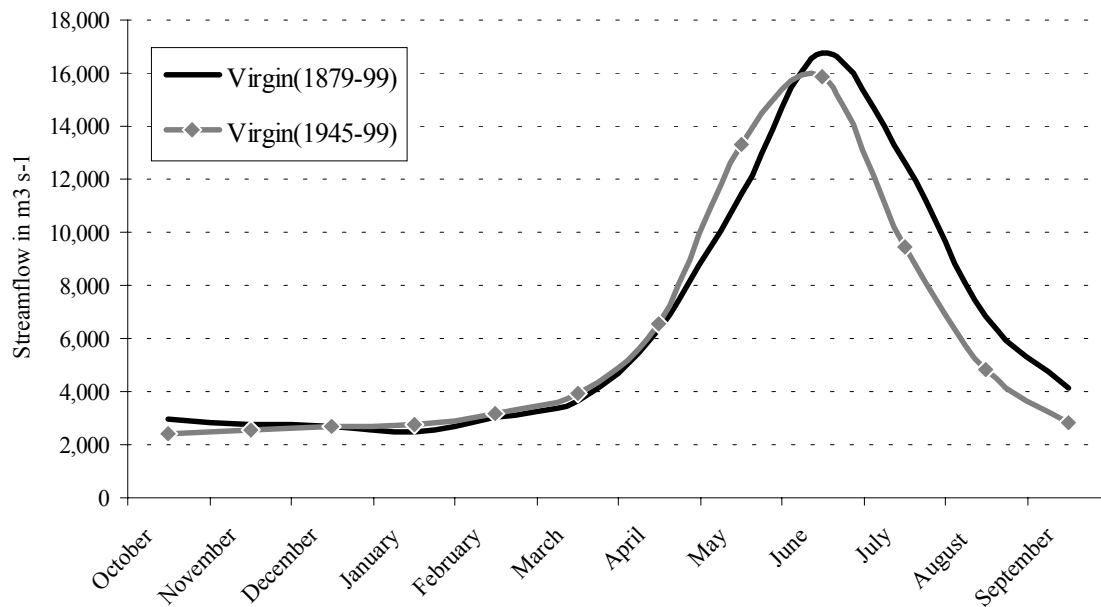

Figure 3.5b. The change in monthly averaged Columbia River interior sub-basin virgin river flow between 1878-1999 and 1945-1999. The spring freshet is now small and earlier, and summer flows are lower.

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The total reduction of annual average flow (difference between 19th-century virgin flow and 1945-1999 observed flow of 5,360 m^3s^{-1}) is 960 m^3s^{-1} or 15.2% (Fig. 3.5b). This is larger than the climate change (7.4%) plus irrigation withdrawal (7.0%). The discrepancy (about 0.8% of the original virgin flow) represents an uncertainty level related to the different averaging periods used in the estimates. If we consider the 1970-1999 period as the present, then the total reduction is somewhat larger, 1,070 m^3s^{-1} or 16.9%. We apportion this net change as follows: climate change (8.9%), irrigation depletion (7.4%), and evaporation/uncertainty (0.5%). The longer averaging period (1945-1999) more realistically represents climate effects; the shorter (1970-1999) period better represents human manipulation.

The annual average flow is not only reduced by human manipulations, but the year when flow occurs may be changed by the storage time of water in reservoirs. The total average flow of the Columbia River at The Dalles is 171.2 km^3, whereas the storage capacity is 77.7 km^3, yielding a ratio of storage capacity to flow of 0.45. Regulation of river flow does not normally result in large interannual transfers of flow, as it would in a basin with a larger storage capacity relative to the total annual water production (e.g., the Colorado River). Nonetheless, interannual transfers of $\pm$ 370-790 m^3s^{-1} occurred in 1974, 1976-1978, and 1992. These interannual transfers decrease the interannual variability of the flow.

Interior Basin Spring Freshet Magnitude and Timing

The above changes in annual average flow are only a small part of the total hydrological changes in the Columbia. Seasonal changes, particularly those in spring freshet timing and magnitude, have been much larger than those in annual average flow. Spring freshets are extremely important for juvenile salmonids in that high flows (especially overbank flows) provide habitat, 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 season is also a major factor maintaining a detritally-based food web, centered in the estuarine turbidity maximum (ETM).

Flows in the Columbia River interior sub-basin (the flow measured at the The Dalles) are primarily driven by spring snowmelt, though there are rain-on-snow freshets in some winters. Before 1900, the highest flows typically occurred during May-July. Monthly Columbia River virgin flows at The Dalles were 11,480 m^3s^{-1} (for May), 16,760 m^3s^{-1} (for June), and 12,600 m^3s^{-1} (for July) during 1879-1899. The corresponding figures for 1945-1999 were 13,300 m^3s^{-1}, 15,840 m^3s^{-1}, and 9,420 m^3s^{-1}; these are changes of +15.9, -9.5, and -25.2%, respectively.

The decrease in July flows and increase in May flows have been caused by the earlier onset of spring freshets (Figs. 3.6a and 3.6b). Also, the May-July average virgin flow for the 1879-1899 period was 13,610 m^3s^{-1}, while it was 12,850 m^3s^{-1} for the 1945-1989 period, a decrease of 5.6%. This represents the freshet-season flow decrease due to climate change.
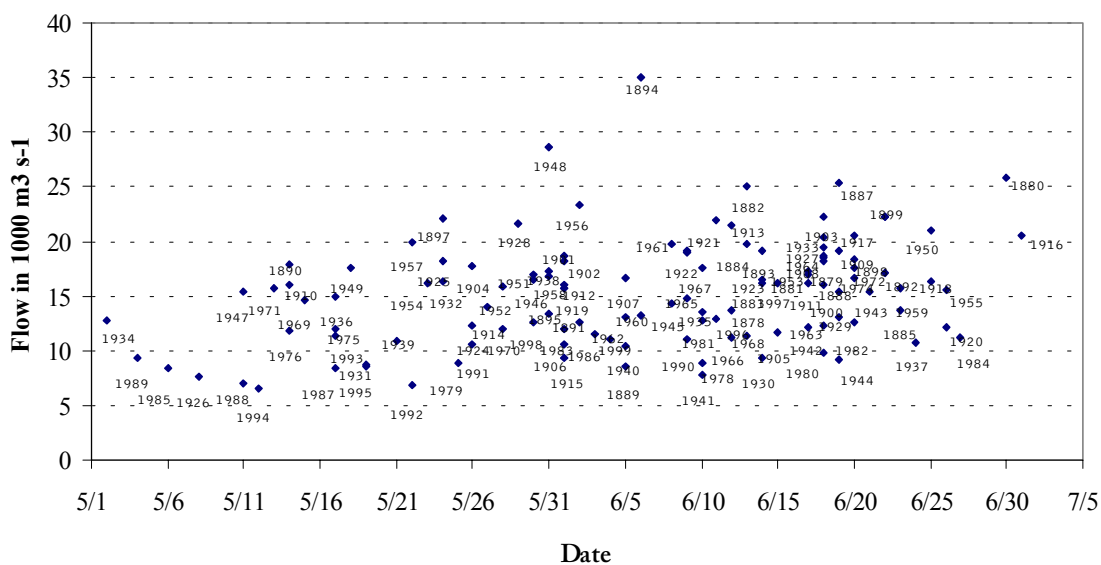
Figure 3.6a.   Seasonal timing and magnitude of Columbia River interior sub-basin freshets (at The Dalles), 1878-1999. The strongest spring freshets (1894 and 1948) involved a rain-on-snow event, and have occurred relatively early in the season. Some but not all very small freshets have occurred in early May.
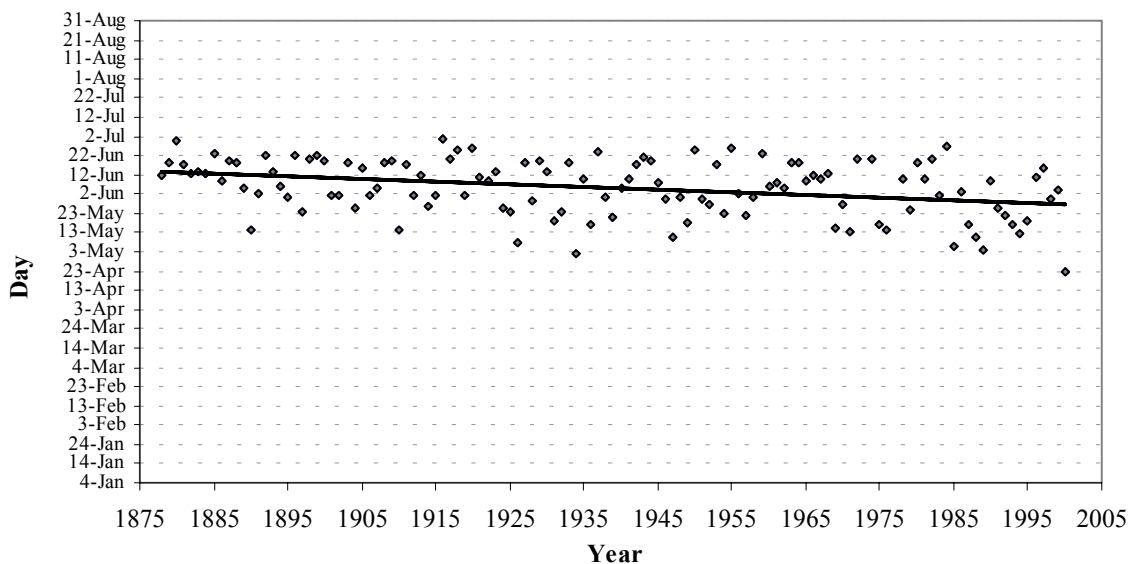

Figure 3.6b. A linear fit to peak freshet day vs. year suggests that the freshet is now about two weeks earlier than in the 19th century.

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Furthermore, note that the January-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 winter, early spring, or late summer and fall.

The present freshet season flow decrease due to water withdrawal can be determined from the 1970-1999 differences between the monthly Columbia River virgin and adjusted flows at The Dalles. These reductions are 750 m^3s^{-1} (May), 1,900 m^3s^{-1} (June), and 1,890 m^3s^{-1} (July), or 5.7, 12.5, and 20.8% of the virgin flow for the period, respectively. The total May to July seasonal decrease due to water withdrawal is about 10.5%.

The present freshet season flow decrease due to flow regulation can be determined from the 1970-1999 differences between the monthly Columbia River adjusted and observed flows at The Dalles. These reductions are 4,100 m^3s^{-1} (May), 4,920 m^3s^{-1} (June), and 1,790 m^3s^{-1} (July), or 31.6, 32.4 and 19.8% of the virgin flow for the period, respectively. The total freshet-season flow decrease due to flow regulation is 3,600 m^3s^{-1} or 29.1% of the present spring virgin flow and 33.1% of the present spring adjusted flow. Flow regulation is clearly the source of the largest reduction in spring flow.

The total reduction in freshet-season (May-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. The present freshet season flow of 7,740 m^3s^{-1} is 148% of the current annual average flow. During the 19th century, freshet flows were about 215% of the contemporary mean.

The reduction in peak flows of freshets has been slightly larger than that of the freshet season as a whole. The observed maximum annual daily spring freshet flow for the period 1858-1899 was 19,300 m^3s^{-1}, which is very close to virgin spring freshet magnitude, because water withdrawals during the 19th century were small. Present (1970-1999) observed annual maximum daily spring freshet flow is 10,870 m^3s^{-1}, 44% less than before 1900. Peak freshet flow for 1945-1999 was 13,530 m^3s^{-1}, 30% less than before 1900. Clearly, freshet reduction was much less effective before 1970.

It is difficult, because of the disparate time scales involved, to separately estimate reductions in daily maximum flow due to climate, irrigation, and flood control. Yet the climate change component is not the largest factor, given the small climate-induced change in the May-July average flows. Present irrigation withdrawal during the spring freshet season is usually less than 1,800 m^3s^{-1}, also small relative to the freshet reduction. Therefore, most of the loss in maximum spring freshet flow is due to flow regulation. Flood control reductions of more than 10,000 m^3s^{-1} occur in high flow years like 1974 and 1997 (Fig. 3.6c). The original maximum daily flow was 305% of the mean, whereas this figure has been reduced to 205% at present.

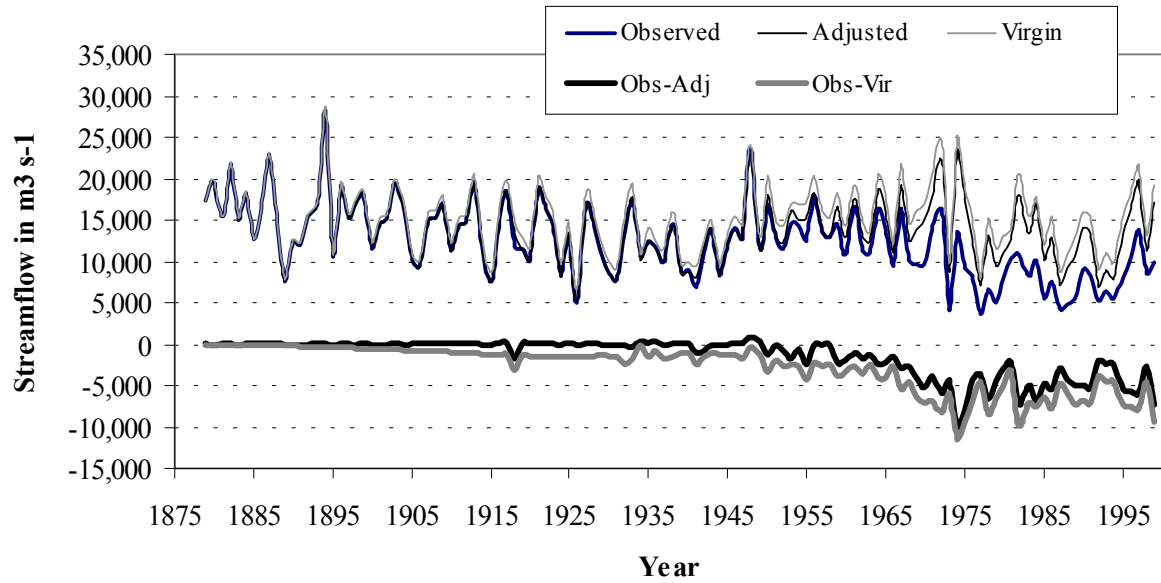**Columbia River mean flow in June: 1879-1999**

Figure 3.6c. Reduction of the monthly mean June flow. The observed-adjusted flow
shows the effects of flood control, while the observed-virgin flow includes
the effects of irrigation depletion as well.

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The role of climate change in reducing freshet magnitude over the last 140 years should not, however, be totally neglected. Even though climate-induced changes in annual average flow have been modest, the annual flow cycle has also changed, probably due to higher average air temperatures. That is, the Columbia has shifted from a state (before 1900) where winter freshets in the interior basin were unusual to a state where substantial flow events occur in many winters.

One result is that there was a greater incidence of very large spring freshets during the last half of the 19th century. We have peak flow information for only 43 years in the 19th century (1849, 1858-1999), yet 10 of the 14 largest known freshets occurred before 1900. This compilation is based upon estimated virgin daily flow, so that direct human manipulation is not the reason for the difference. Similarly, the four largest known freshets in the Willamette River occurred in the 19th century.

The timing of the maximum spring freshet flow has also changed (Fig. 3.6b). 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 (as determined by wavelet transformation of the flow data), 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. That is, irrigation withdrawal usually peaks in June, which tends to further curtail the freshet.

The relative size of these three effects on freshet timing cannot in general be determined. However, the very early 2000 freshet peak on 23 April (the only April freshet ever recorded) occurred largely as the result of flow regulation.

Changes in Western Sub-Basin Flows

The interior sub-basin flow at The Dalles described above accounts for ~75% of the total flow to the estuary. Flows in the Willamette River are typical of the remaining 25% from the western sub-basin. The Willamette is the largest river in the western sub-basin, with about 60% of the western sub-basin flow, or 15% of the total flow for the basin. Climate influences on the Willamette are likely very similar to those on other western sub-basin tributaries (e.g., the Cowlitz, Kalama and Lewis Rivers) draining the west side of the Cascade Mountains, although the Cowlitz has a larger contribution from seasonal snow pack, and anthropogenic effects are system-specific.

The Willamette River responds primarily to winter rainfall and melting of recently deposited snow, with only modest storage of water in seasonal snowpack and glaciers. The largest freshets in the system are caused by winter, rain-on-snow events. The Willamette River basin is much smaller than the interior sub-basin, and its flows are not as heavily regulated.

For these reasons, and because the Willamette Basin area is small relative to that of synoptic weather events, Willamette River flows are much more variable on short time scales than those at The Dalles (Fig. 3.7).

The observed annual average Willamette River flow at Albany has decreased from 460 m^3s^{-1} for 1893-1900 to 418 m^3s^{-1} for 1945-1999 and to 390 m^3s^{-1} for 1970-1999; decreases of 9.5 and 14.8% respectively. It is not possible to separate the components into losses associated with climate and water withdrawal. We also do not know the irrigation withdrawal before 1900. Nonetheless, it appears that historical changes in annual average flow have been smaller in the Willamette than in the interior sub-basin.

The seasonality of Willamette River flow at Albany has been altered by climate change, the irrigation cycle, and flow regulation for flood control (Fig. 3.8). Late summer to early winter flows (August to December) have been augmented (comparing the historic and modern flows), likely by irrigation return flow and by pre-release of any surplus water before winter. Average monthly flows during the January to July periods have decreased, especially those in January and February, when the reduction has exceeded 120 m^3s^{-1}, out of the original ~920 m^3s^{-1}. The decrease in mid-winter average (and extreme) flows is likely due to a combination of climate effects and flood control. The difference between the historic and modern flows peaks again in May, at more than 120 m^3s^{-1}. Irrigation and storage of water for summer power generation are likely reasons for the spring flow decrease. However, the seasonal snow pack may also be smaller.

River Flows at the Head of the Estuary

The best measure of total mainstem freshwater input at the head of the estuary is the flow at Beaver. Flow properties at Beaver are the sum of those for the interior and western sub-basins (Fig. 3.9). The long-term average annual flow (1892-1999) at Beaver is 6,960 m^3s^{-1}. Taking into account the very high flows observed at The Dalles for 1878-1891, we estimated that the average flow during this period at Beaver was about 7,060 m^3s^{-1}.

It is not possible to separate climate, flow regulation and water-withdrawal effects on the flow at Beaver, but the average flow is now substantially lower than it was. The average annual flow, for example, for 1892-1902 was ~8,300 m^3s^{-1}. Reflecting the alteration of interior basin flows, the spring freshet at Beaver has become longer, weaker, and earlier, while winter flows are less sharply peaked than before flow regulation. Monthly average winter flows are, however, slightly larger than before 1900 (Fig. 3.10). There are no long-term sediment transport estimates available for Beaver.

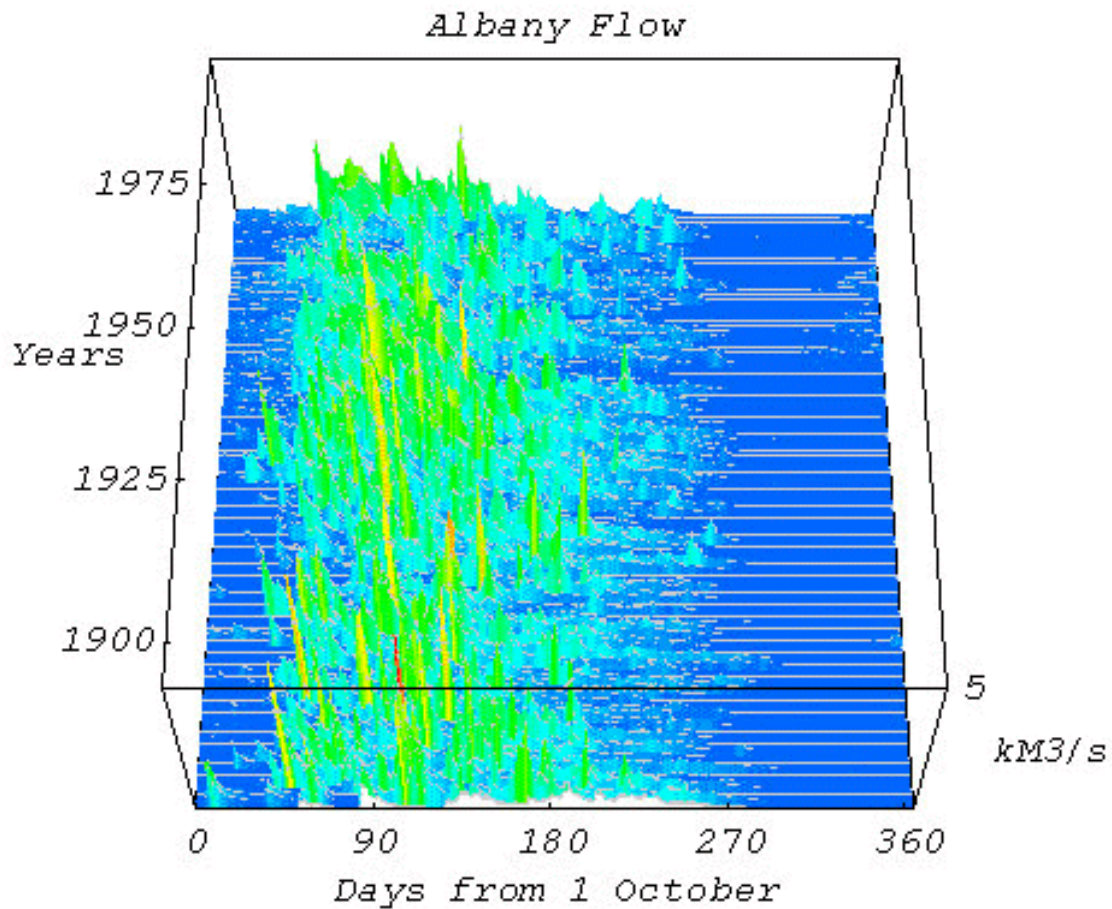*SARE draft: Hydrological Conditions*

Figure 3.7. Observed daily Willamette River flow at Albany, 1893-1998; this flow is representative of the western sub-basin. Note the reduction in magnitude and sharpness of winter flood peaks. A floor has been set at 200 m^3 s^{-1} to emphasize high flow periods.
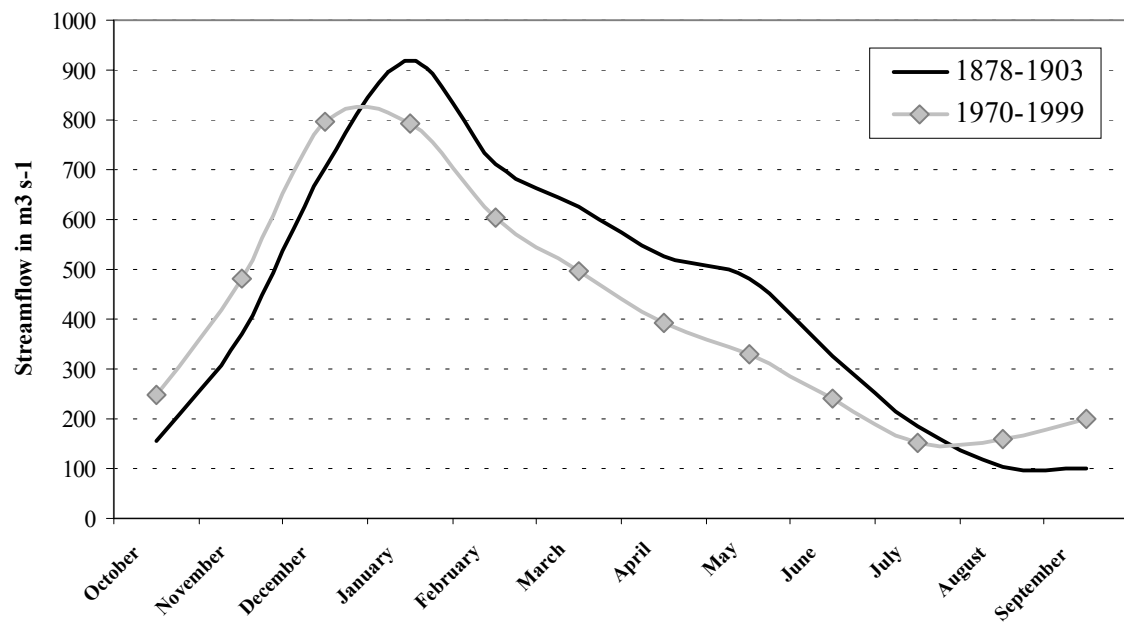
Figure 3.8. Historical changes in the annual flow cycle of the Willamette River at
Albany, 1878-1903 (some data missing) vs. 1970-1999.

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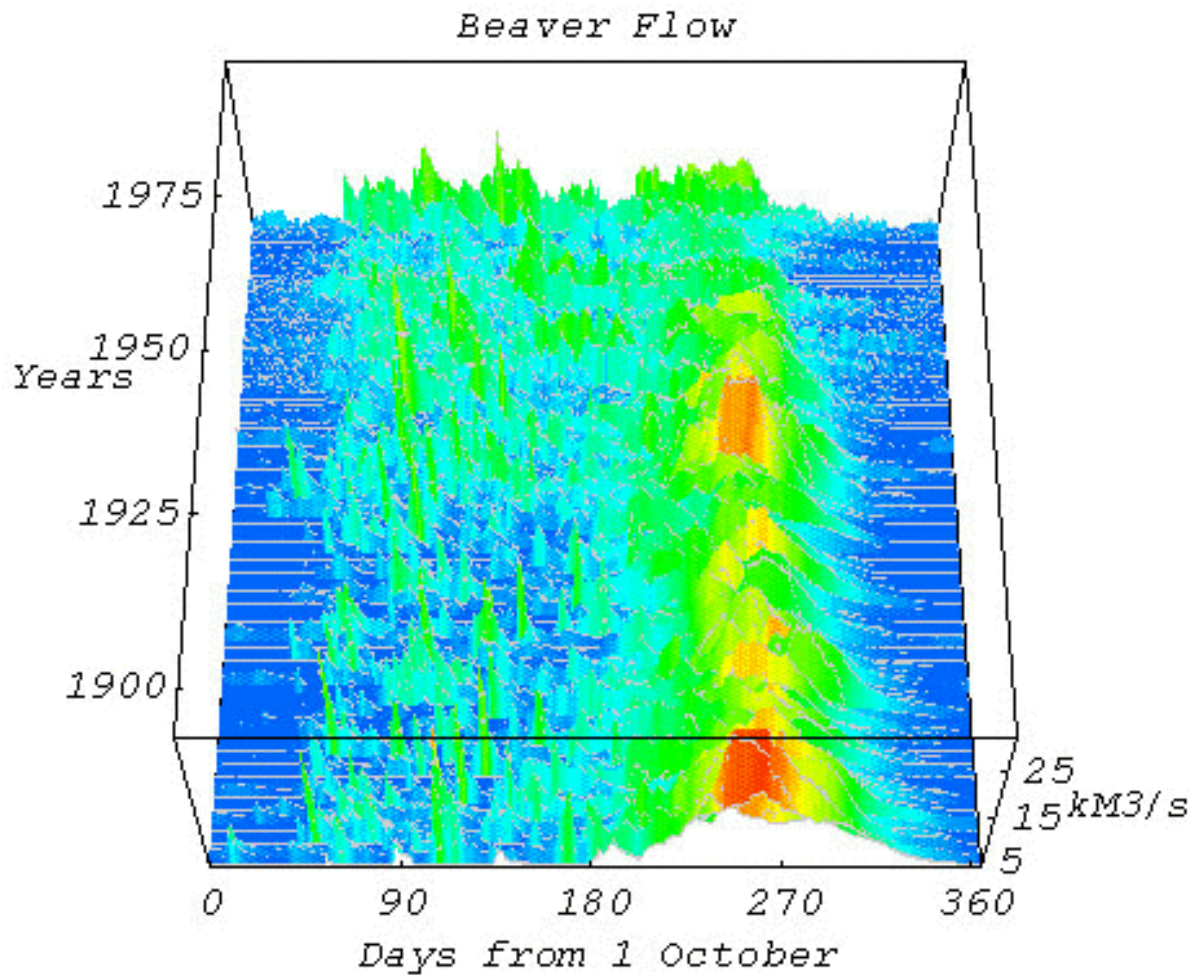
Figure 3.9. Estimated total observed daily Columbia River flow at Beaver, 1892-1999. Note the combination of characteristics derived from the interior and western sub-basins. A floor has been set at 4,000 m^3 s^{-1} to emphasize high flow periods.
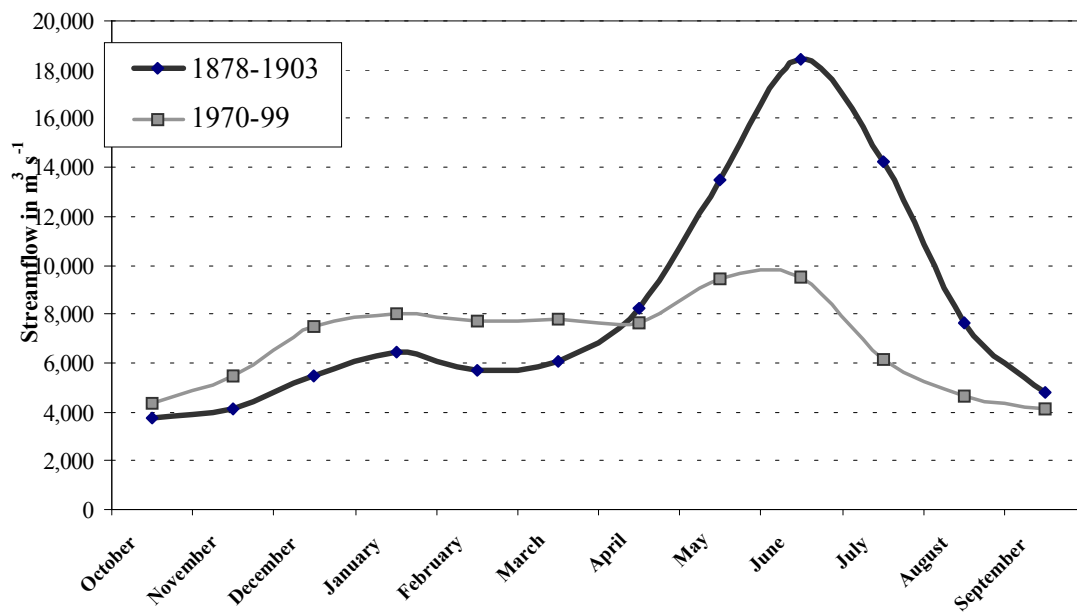
Figure 3.10. Changes in the annual flow cycle of Columbia River flow at Beaver, 1878-1903 (some data missing) vs. 1970-1999.

Flows from Estuary Tributaries

The flow at Beaver is not the total flow of the Columbia River. There are also several smaller rivers directly tributary to the estuary seaward of Beaver, for example the Elochoman, Youngs, Lewis and Clark, and Grays Rivers. These rivers contribute an estimated annual average of only 3% of the total flow at the river mouth, or ~230 m^{3}s^{-1} (Orem 1968). Their contribution during winter storms is likely much higher but has not been systematically assessed.

Little is known regarding historical changes to the hydrological properties of the estuary tributaries, and no systematic sediment transport records are available. Several of these tributaries were severely disrupted, however, by downstream transport of logs to tidewater during early logging operations.

Total Columbia River Flow at the Mouth

The total annual average flow at the mouth of the Columbia River may be estimated by adding the long-term average for Beaver to the estuary tributary flow. The result is ~7,300 m^{3}s^{-1} for the period 1892-1999. This is somewhat smaller than the figure (7,720 m^{3}s^{-1}) given by Orem (1968), because a) Orem used primarily data from a cold-PDO phase of elevated flows (1943-1957), and b) the average observed flow has decreased slightly since Orem's work was published.

Finally, the value of the Columbia River flow at the mouth prior to 1900 was less than 8,500 m^{3}s^{-1}, but has decreased to ~7,080 m^{3}s^{-1} (1970-1999). No estimates of total sediment transport from the Columbia River to the continental shelf are available.

Human and Climate-Induced Changes in Sediment Transport

Sediment transport is a vital system characteristic for salmonids in several respects. The organic component of the fine sediment supply (silts and clays) supports a detritus-based food web that now provides the bulk of estuarine secondary productivity in the system (Simenstad et al. 1990, 1995). The turbidity caused by fine sediment may hinder predation on juvenile salmonids, but excessive levels may be injurious to juveniles and damage spawning habitat. The coarser fractions (sands and gravels) are vital both to natural habitat construction in the estuary and to maintenance of spawning habitat higher in the basin.

Dredging and disposal of sands and gravels have, over the last century, been one of the major causes of estuarine habitat loss. For scientific reasons, it is important to distinguish between the fine and coarse sediment fractions. For methodological reasons, sediment transport is reported in terms of "total load" (all fractions) and sand (implicitly including gravel as well).

Daily sediment transport data (at Vancouver and/or Beaver) for the interior sub-basin are available only for 1963-1970. We have, therefore, hindcast total load and sand transport at Vancouver for the entire period (1878-1999) of the daily flow record at The Dalles, estimating the sand fraction based on measurements described in Haushild et al. (1966). This calculation has been carried out for both the observed and virgin flow (Fig. 3.11). Willamette River total load has been hindcast for 1892-1999 on the basis of 1910-1913 and 1962-1963 sediment transport data.

Implicit in these hindcast transports for the two systems is the assumption that land use and channel development have not materially altered sediment transport. Sand and gravel movement is, in fact, transport-capacity limited; material is always available on the bed and will move whenever flow conditions are suitable. We expect, therefore, that the sand-transport estimates are nearly as accurate as the flow estimates, at least within the limited flow range of the data set used to calibrate sand transport. In contrast, transport of fines is supply-limited; normally the capacity to move the material is greater than the supply.

Clearly, timber harvest, agriculture, and urban development have affected the supply of fine material. As discussed below, there is also evidence that the supply of fines is a function of "freshet style" as well as flow volume; that is, the amount of fine sediment depends on the source and timing of the flow. Still, a consistent estimate of sediment transport that is not influenced by land use has some advantages: it brings out clearly the climate fluctuations and human manipulation of the flow cycle.

The effects of climate change on interior sub-basin total sediment supply can be determined by considering historical changes in sediment transport associated with virgin flow at The Dalles. The hindcast total load (sand plus finer fractions) associated with The Dalles virgin flow was 20.5×10^6 t for 1879-1899. Annual average sediment transport (estimated from maximum daily flow) was 21.2×10^6 t during the period 1858-1878. Therefore, the annual average sediment transport for the 1858-1899 period was $\sim 20.8 \times 10^6$ t.

The hindcast annual average total virgin flow sediment transport was 17.2×10^6 t for 1945-1999. Thus, the decrease in total sediment transport due to climate change was $\sim 3.6 \times 10^6$ t or $\sim 17\%$. This is considerably larger than the climate-driven change in flow for two reasons: a) sediment transport varies with a power n of the flow, $n = \sim 2.5$, and b) decreased mean flow also reflects decreased flow variability and a decreased incidence of the very high-flow days that transport most of the total load.

The decrease in sand transport due to climate change can be determined from hindcast annual average sand transport associated with the virgin flow at The Dalles. This was 10.9×10^6 t for 1879-1899 and 9.8×10^6 t during the 1858-1878 period, giving an 1858-1999 average of $\sim 10.4 \times 10^6$ t. The hindcast annual average sand transport was 8.3×10^6 t for 1945-1999. Thus, the decrease in sand transport due to climate change
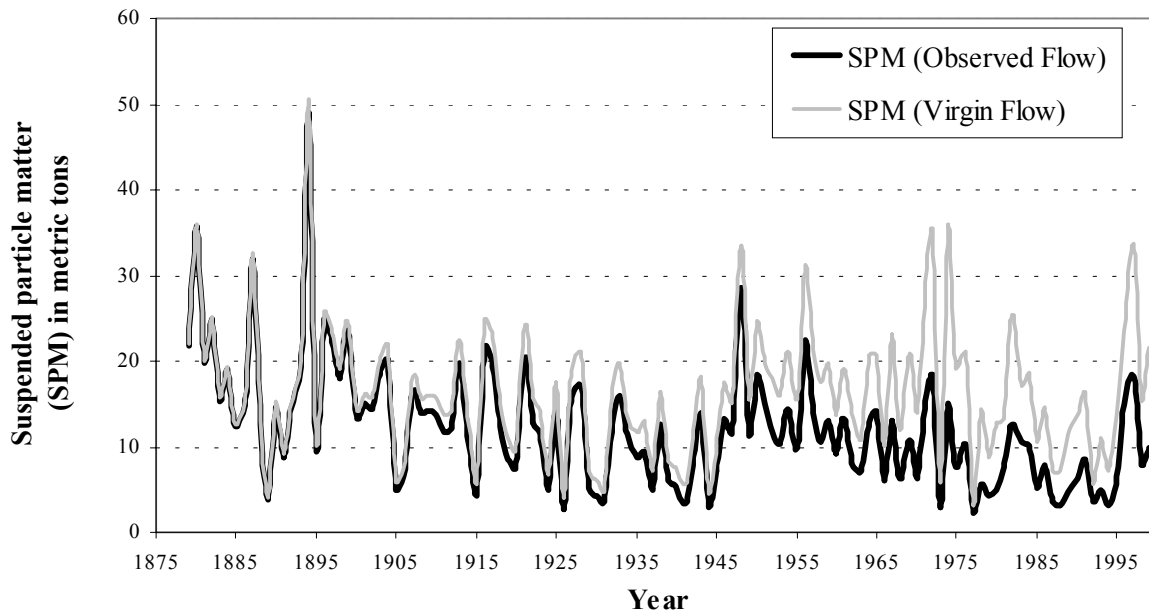
Figure 3.11. Hindcast total sediment load for the Columbia River interior basin
associated with the observed flow and estimated virgin flow. The two are
very similar before 1900, but the sediment transport hindcast from the
observed from after about 1970 is much smaller than the virgin flow
sediment transport, because of flow regulation and water withdrawal.

was 2.1 x 10^6 t or ~20%. The percentage decrease in sand transport is larger than that in total sediment transport, because the percent sand in the total sediment load increases as flow increases.

The average sediment transport associated with the observed 1945-1999 flow was ~10.0 x 10^6 t, whereas that associated with the 1970-1999 observed flow was ~8.0 x 10^6 t. Therefore, the difference between annual average sediment transports at Vancouver for the 1858-1899 virgin flow and 1945-1999 observed flow was 10.8 million x 10^6 metric or 52% of the 19th-century sediment transport. The difference between annual average sediment transports for the 1879-1899 virgin flow and 1970-1999 observed flow is ~12.5 x 10^6 t or 61.5% of the 19th-century sediment transport.   The sand transport associated with the 1945-1999 observed flow was ~3.2 x 10^6 t. Therefore, the difference between annual average sand transport for the 1879-1899 virgin flow and 1945-1999 observed flow was ~7.7 x 10^6 t or ~71% of the 19th-century sand transport.

Because sediment transport is related to flow in a non-linear way, it is not possible to precisely apportion the reduction in sediment transport between climate change, water withdrawal, and flow regulation. The largest single factor is, however, reduction in spring freshet flow for power generation, flood control, and irrigation.

The reduction of western sub-basin winter freshets by climate change and flow regulation has also decreased sediment transport. Hindcast Willamette River total sediment transport for 1893-1903 was 2.4 x 10^6 t, whereas it was only 1.5 x 10^6 t for 1970-1999, a reduction of ~35%. It is not possible to separate human and climate effects in this estimate. Moreover, the Willamette River channel has been more heavily altered (by straightening and elimination of backwater areas, possibly increasing transport capacity) even than the Columbia River channel. The effects of agriculture and urban development have also been pervasive in the Willamette River valley. This may indicate that hindcast estimates are less useful in the Willamette than the Columbia. Nonetheless, no systematic difference was found between the 1910-1913 and 1962-1963 sediment transport observations for the Willamette.

Human and Climate Effects on Disturbance Frequency

The frequency and magnitude of disturbance to the river system is important to salmonids for several reasons. Overbank flow contributes large woody debris that helps to structure fluvial and estuarine environments. The bulk of the sediment input to the system also occurs during high-flow events; this is especially true for the input of sand that helps to build shallow-water estuarine habitats. We therefore examine extreme flows and relevant geological processes on time scales from geological to historic.

Extreme Events

Extreme geological events such as volcanic eruptions, subduction zone earthquakes, and major landslides have shaped the evolution of salmonid stocks in the Columbia River. The largest disturbances occur very infrequently, but may influence salmonid survival for decades, centuries, or even millennia after their occurrence. The post ice-age floods before 10,000 YBP (years before present), for example, totally altered the landscape over large parts of eastern Washington and greatly influenced the form and habitats of the lower Columbia River and estuary.

Other catastrophic events, for example, the Bridge of the Gods rockfall into the Columbia River, have occurred since the stabilization of sea level, around 6,000-7,000 YBP. Blocking or nearly blocking the Columbia River for a time near Cascade Locks, the Bridge of the Gods must surely have influenced salmonid distributions and native utilization of fish in the interior sub-basin.

Changing climate conditions, including fluctuations in seasonal temperature patterns over centuries to millennia, have affected salmonid populations throughout the Pacific Northwest (Chatters and Hoover 1986, 1992). For example, the time period 10,000-9,000 YBP was characterized by cold winters and hot summers, 9,000-8,000 YBP by warm winters and hot summers, 4,400-3,900 YBP by warm winters and cooler summers, 3,900-2,400 YBP by cold winters and cool summers, and 2,400-1,800 YBP by warmer winters and warmer summers.

During the period from 120 to 1029 AD, floods deposited significant quantities of sediment downstream from Grand Coulee Dam approximately every 84 years, less often than at present. A warming period from 900 to 1300 AD caused montane glaciers to recede and increased flood frequency; from 1020 to 1390 AD major floods were three times more frequent than between 120 and 1029 AD. Distinctly cooler and/or moister climatic conditions than at present also occurred from ~1350 to 1900 AD. The period from about 1500 to 1850 AD is sometimes known as the "Little Ice Age."

Very large subduction-zone earthquakes have occurred approximately every 300-1,000 years; the last major event occurred in 1700. These earthquakes are known to be associated with large rockfalls, landslides, and tsunamis in inland waters (e.g., Puget Sound and Lake Washington). Large but unknown effects on sediment transport in the Columbia River must have resulted. Estuarine habitat conditions also changed dramatically following subduction zone earthquakes, which typically caused the coast to subside 0.5 to 1 m. Other events resulting in large sediment inputs, for example, the eruption of Mount St. Helens, are perhaps not as rare as one might judge from their rate of occurrence in the 20th century. Mount St. Helens has been active three times since 1790, and major mudflows occurred on Mount Hood between 1790 and 1800.

Historical Changes in Overbank Flow

We now consider the historical record of major flow events. The historic bankfull flow level is estimated at about 18,000 m^{3}s^{-1} for the main stem below Vancouver. This is the 2-year flow recurrence level for The Dalles, augmented by the typical spring-flow level for the west side tributaries. Modern bankfull level is set by the standard project flood level of ~24,000 m^{3}s^{-1} for the lower river. Some overbank flow occurred in many years before 1900, both in winter and in spring (Fig. 3.12a).

Substantial overbank flow (above 24,000 m^{3}s^{-1}) is now rare, with significant events occurring only five times during the last half century--in 1948 (spring), 1956 (winter and spring), 1964-1965 (winter), and 1996 (winter). Today, even historical bankfull levels of 18,000 m^{3}s^{-1} are rarely exceeded due to effects of flood control measures and irrigation depletion. The season when overbank flow is most likely has also shifted from spring to winter, because western sub-basin winter floods (not interior sub-basin spring freshets) are now the major source of such flows.

Climate is a secondary factor in the incidence of overbank flow. Overbank flow events were clearly 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 (Fig. 3.12b). Flood protection, diking, flow regulation, and water withdrawal have, however, largely eliminated climate influence on overbank flow. Overbank flow is now rare even during cold-PDO phases, and it was totally absent during the last PDO warm phase (1977-1995).

Changes in the River Flow Frequency Distribution

Another important symptom of human intervention in the flow cycle is the change in the frequency spectrum of the flow. There are two convenient ways to examine this spectrum: a) the power spectrum (related to the Fourier transformation of the time series of flow) gives a high-resolution picture of the average frequency content of a process over a period of time, and b) the wavelet transformation gives a less detailed view of the time-dependence of the frequency content.

Comparison of the power spectra for the 1878-1910 and 1970-1999 periods defines the nature of the changes that have occurred (Fig. 3.13). Low-frequency flow variations with periods between ~2 years and 6 months have been suppressed, whereas high-frequency variations associated with power peaking have been greatly augmented. Aside from a slight decrease in the annual cycle, these changes are not related to climate, as the virgin flow spectra for the two periods are very similar.

The daily power peaking cycle also perturbs the diurnal (daily) tidal signal in the river, and this effect can be seen at least as far seaward as Beaver. The wavelet presentation of the flow spectrum (Fig. 3.14) shows: a) the truncation of the annual flow
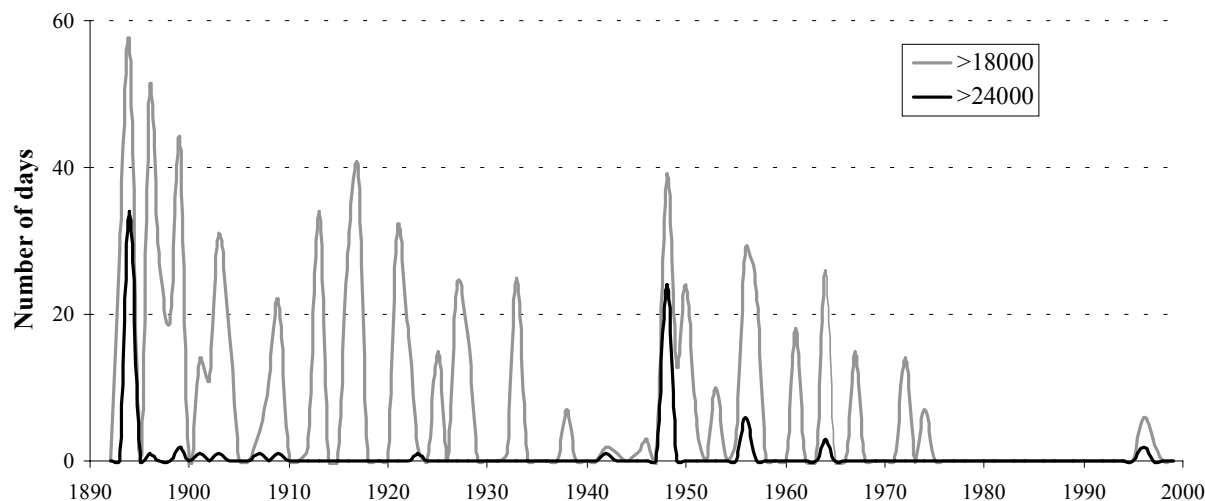
Figure 3.12a. The incidence of flows above 18,000 m^3s^{-1} (the pre-1900 estimated bankfull flow level) and above 24,000 m^3s^{-1} (the present bankfull flow level). The present bankfull flow level has only been exceeded in four years since 1948.
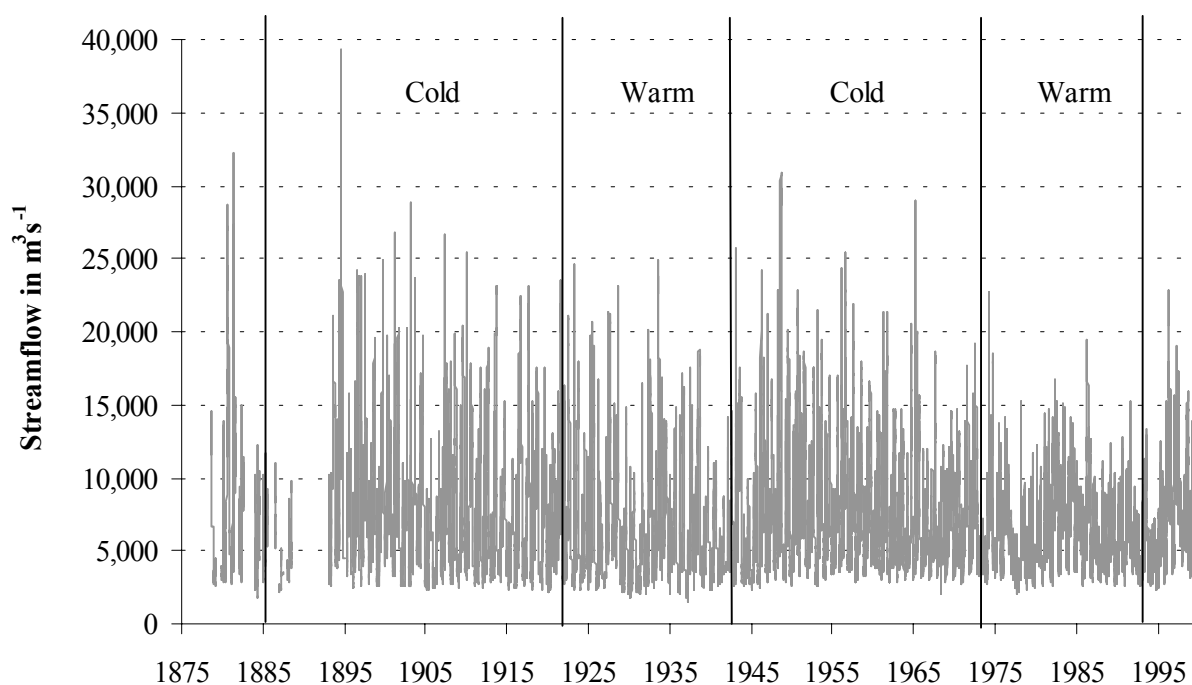
Figure 3.12b. Monthly average flows at Beaver (1878-1999), present and historical bankfull flow levels, and warm and cold-PDO cycles. Historically, there was a major difference between the warm and cold phases of the PDO cycle in disturbance frequency. This has been largely eliminated by flow regulation and diking; overbank flow is now a rare event.

Figure 3.13.   Power spectra of The Dalles observed daily flow 1878-1910 and
1970-1999. The peaks at 1 year and 6, 4, and 3 months, clearly visible in
the 1878-1910 record, have been greatly reduced by flow regulation and
irrigation depletion. The power peaking cycle has added energy to the
system at frequencies above ~20 days, but especially at 7 and 3.5 days.
Also shown are 95% confidence limits.

The Dalles Observed Flow, 1000 m3/s
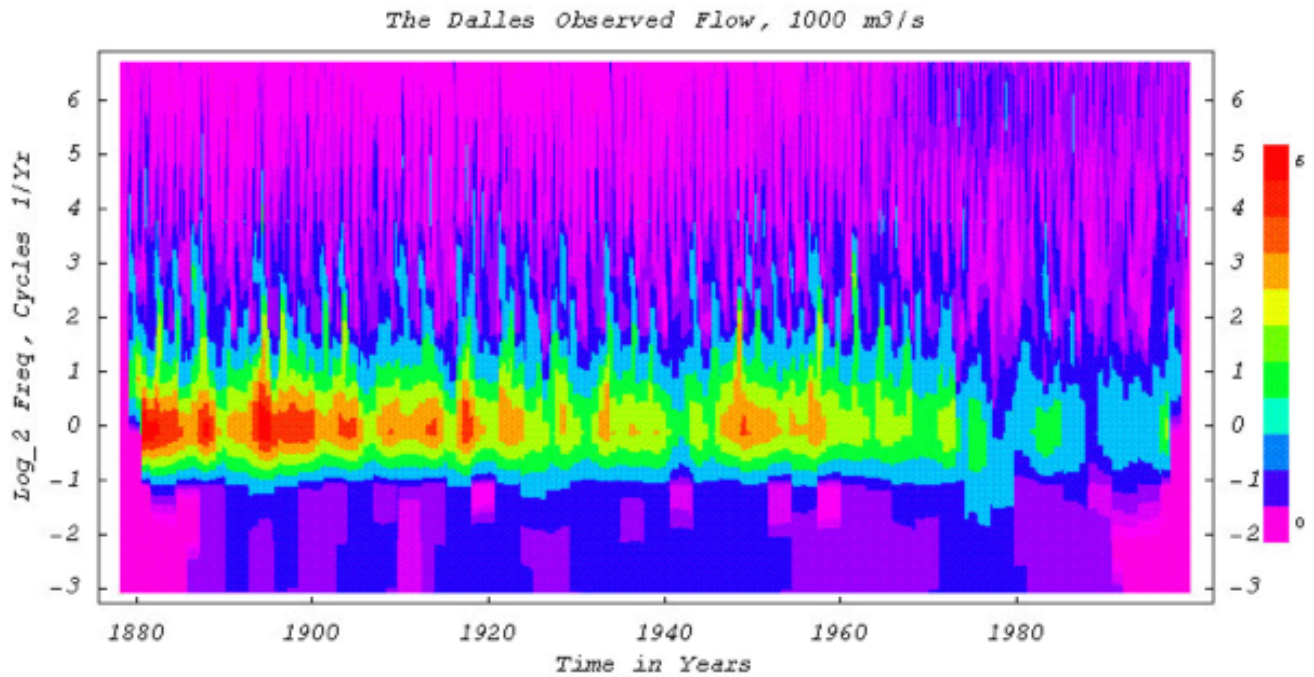
Figure 3.14. Scaleogram of observed flow at The Dalles. Time in years is on the x-axis, and log (base 2) of frequency in cycles per year is on th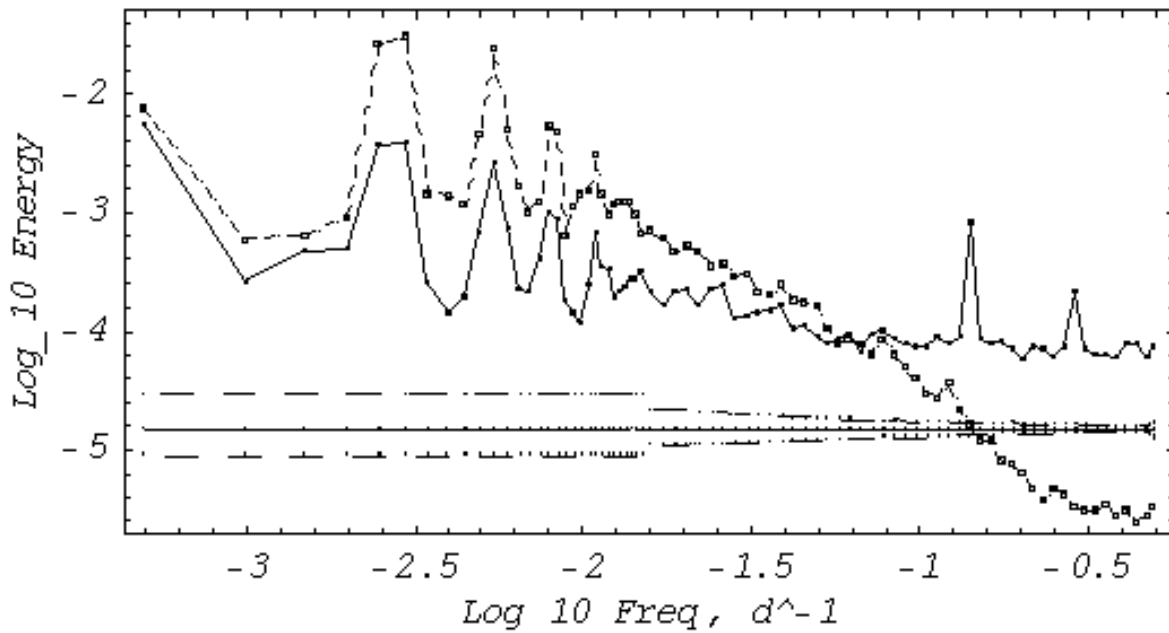e y-axis, showing periods of 8 years (bottom) to 3.5 days (top). Thus, the annual cycle is denoted by $\log_2$(frequency) = 0 (1 cycle x year^{-1} or 2^0= 1), and a period of 6 months by $\log_2$ (frequency) = 1 (2 cycles x year^{-1} or 2^1 = 2). Irrigation depletion begins to affect freshet strength and the annual flow cycle noticeably after 1920. Flow regulation effects are evident in the 1960s and dominant after 1970. High-frequency power peaking (periods of 3.5 and 7 days) is evident after ~1970.

cycle by flow regulation after ~1970 (despite very high virgin flows in 1972 and 1974), b) a sharp increase in high frequency energy associated with the hydroelectric operations after ~1965, and c) a climate (PDO cycle) influence on freshet strength (e.g., spring freshets were unusually low during ~1922-1944 and higher again 1945-1976, despite flow regulation).

Climate and Human Influences on Freshet Styles

The flow cycle is different each year, but despite this diversity there are definite patterns. It is useful to describe "freshet styles" that represent frequently occurring types of flow events, and to examine human and climate influences on these freshet styles. Because freshet styles strongly affect flow and sediment transport patterns in both tributaries and the main stem, they may have substantial, as yet unidentified, effects on salmonids. There are three kinds of spring freshets in the Columbia River, distinguished by the source of flow:

> *Large winter snow pack without exceptional spring rain*--For example, 1880, 1916, 1972, 1974, and 1997. Very late spring freshets are likely to be in this category.

> *A normal winter snowpack followed by a very wet spring*--The result is heavy snow in April and early May and then very heavy spring rains that rapidly melt an unconsolidated snowpack; 1948 is an example.

> *A large winter snow pack AND heavy spring rains*--1894 is the only certain example of this category (Paulsen 1949), although some of the other very high spring freshets of the 19th century were likely of this sort also, for example, 1849 (the second highest known freshet, intermediate between 1948 and 1894).

Heavy spring rains in 1894 and 1948 accelerated the spring freshet so that the maximum flow was not unusually late, even though a cold spring had allowed the low-elevation snowpack to continue to grow up to the onset of the freshet. Winter freshets caused by rapid snow melt and thawing of poorly vegetated interior sub-basin soils are known to cause unusually large sediment transport (Waananen et al. 1971). This may also be the case for spring freshets, but data are not available to test this hypothesis.

All major winter freshets in the Columbia Basin are the result of rain-on-snow events that cause rapid melting of a low elevation snow pack. There are three types of winter freshets, based on the location of the low-elevation snow pack that is melted:

> *Primarily western sub-basin*--For example 1894 and 1965.
> *Interior and western sub-basins*--For example 1861, 1881, and 1996.
> *Interior sub-basin only*--December 1933 is the best example, although Cowlitz River flows were somewhat elevated.

SARE draft: Hydrological Conditions

All of these freshet types require that a low elevation snow pack be melted by a "Pineapple Express" storm. If there is no low-elevation snow pack, there will not be a major winter freshet, no matter how intense the storm.

Winter freshets are spatially more diverse than spring freshets, because winter freshets are primarily a response to a specific storm or series of storms, with attendant large spatial variability. For example, 1933-1934 winter storms affected the Wenatchee River and tributaries very strongly. Flows in 1881 were very high in the Willamette and Umatilla Rivers. Furthermore, the Canadian part of the basin usually plays only a minimal role in winter freshets, because high temperatures do not penetrate to this part of the basin during most storms.

While there are certainly spatial differences in total winter snow pack between sub-basins, spring freshets are more similar from year to year because they represent an average over the entire winter of storm intensity. Winter freshets are, as already noted, a very potent source of sediment.

Flow regulation is most effective in controlling freshets related solely to the spring melting of a large winter snow pack, because a planned pre-release of water can begin in December or January, five to six months before the onset of the freshet. It is much more difficult to anticipate or predict the occurrence of very heavy spring rains, and little preparation can be expected for such events. Winter freshets are also difficult to control, especially when they originate largely in the western sub-basin, where precipitation rates are higher and storage capacity relatively low. Flow from rain-on-snow events, whether in the winter or the spring, is more difficult to control than the normal spring snow melt, because the melt rate is higher.

Warming of the climate over the last century and flood control have reduced the intensity of flow resulting from winter rain-on-snow events in the western sub-basin. Flows in the Willamette River were much higher during the winters of 1813, 1861, 1881, and 1890 than in any 20th-century winter freshet. Maximum flow during the freshet of 1996 was, for example, only ~53% of that estimated for 1861, the largest known event. Newspaper accounts from the 19th century indicate that there was sometimes over 1 m of snow on the ground in the Willamette Valley, a rare event since 1900. The incidence of winter freshets that affected both the western and interior sub-basins may, however, have increased over the last century. Spring freshets related to heavy spring rains are uncommon, and it is not known whether their incidence has changed.

<div align="center">**Downstream Effects of Hydrological Alterations**</div>

Salinity Intrusion and Salinity Stratification

Salinity intrusion length and density stratification due to vertical salinity gradients have both likely increased over the last century. Salinity intrusion is governed by three primary factors: a) maximum channel depth, b) the strength of the tides, and c) river flow. The dependence of salinity intrusion on the channel controlling depth (H) is very strong. The landward nearbed mean flow that drives salinity intrusion varies with the H^2 or H^3, and the dependence of salinity stratification is even stronger, H^4 or H^5. The tides have a complex effect on salinity, because tide-induced vertical turbulent mixing inhibits salinity intrusion, while horizontal transport by the tides is the primary salt transport mechanism during periods of strong tides and low-to-moderate river flows.

Salinity stratification increases with river flow, whereas the relationship between salinity intrusion length (L_S) and river flow (Q_R) is inverse $L_S \sim Q_R^{-n}$, values of n are generally less than 1 but vary from system to system. While this might suggest that the river flow influence is smaller than other factors, it should be remembered that river flow may vary seasonally by an order of magnitude.

Before flow regulation, the possible range of observed flow variation was even larger, ranging from ~1,000 to 35,000 m^3s^{-1} at The Dalles. In contrast, the tidal range varies by only a factor of about 2 over the neap-spring cycle, the tidal prism has been reduced by ~15% by diking and filling, and the controlling channel depth has doubled over the last 120 years. On the whole, changes in bathymetry have likely caused the largest changes in salinity intrusion and density stratification (Fig. 3.15), but reduction of the spring freshet has also increased salinity and salinity stratification. The effects of these changes in salinity intrusion length and stratification on salmonids are not known. New observations and model studies will be needed to clarify this issue.

Habitat Availability

River stage increases more than linearly with river flow. Reduction of maximum flow levels, dredged material disposal, and diking/flood protection measures have essentially eliminated overbank flow (Fig. 3.12) in the estuary and the tidal-fluvial part of the system below Bonneville Dam. This absence of overbank flow has greatly reduced habitat opportunity during the freshet season by limiting flow over the historic flood plain and into areas that were previously forested swamp or other types of seasonal wetland. This loss of habitat needs to be quantified through mapping of historical changes and numerical modeling of present vs. historical flood events.
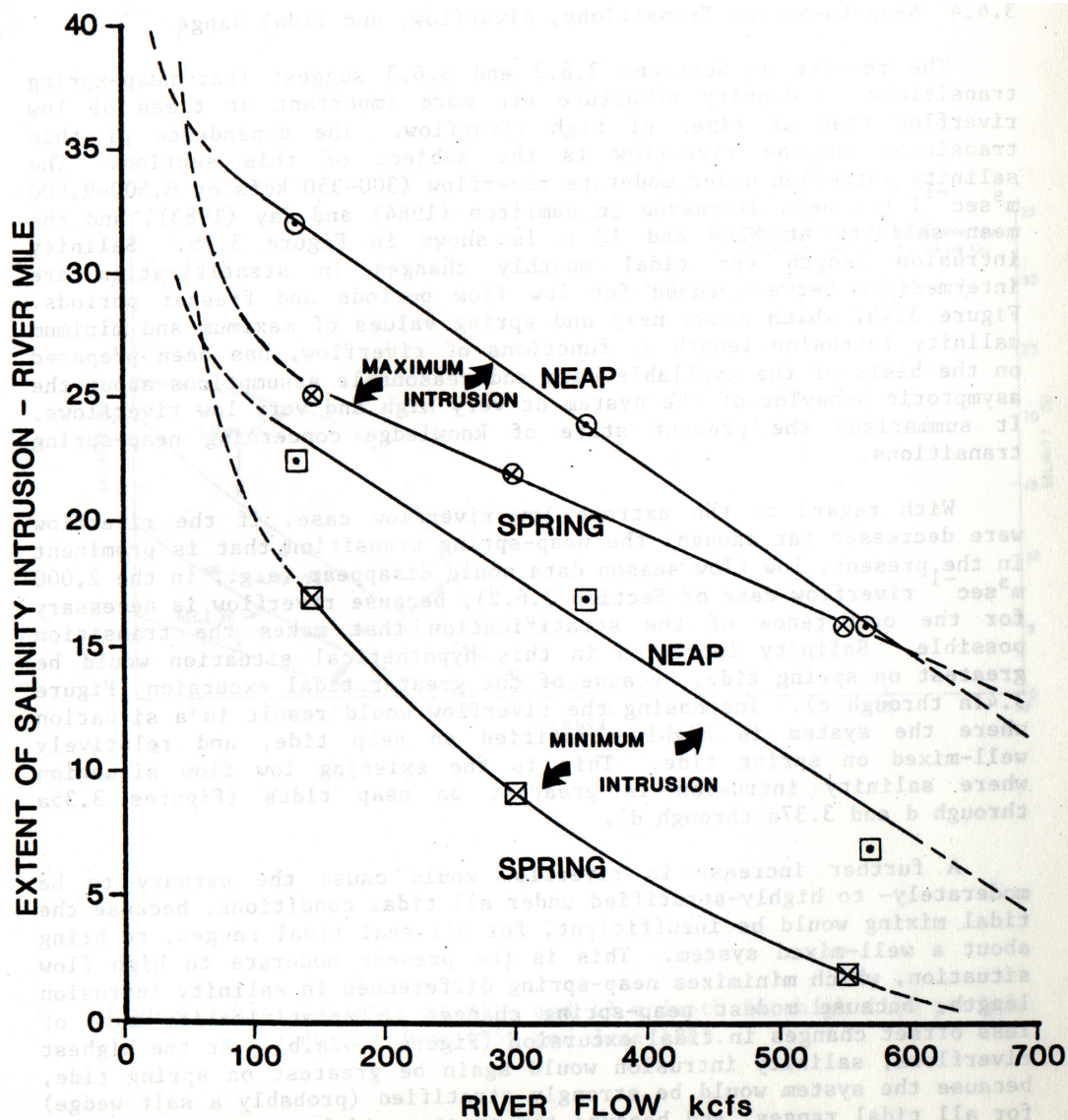
Figure 3.15. Maximum (end of flood) and minimum (end of ebb) salinity intrusion
distance in the Columbia River estuary, based on 1980 bathymetric
conditions (from Jay, 1984). Present salinity intrusion may be somewhat
different, because of deepening of the navigation channel at the entrance.

The Tidal Regime

River flow and tidal propagation interact strongly. The major components of the tide are damped at stations landward of the estuary in proportion to $Q_R^{1/2}$. The distortion of the tide that determines the timing of high and low waters is more strongly affected. Power peaking further complicates river tides by adding "pseudo-tides" (with frequencies close to tidal frequencies) that propagate seaward from Bonneville Dam (rather than landward from the ocean). This effect can be larger than the natural tide landward of Portland. Changes in the seasonal flow cycle have increased tides and tidal currents in the spring and early summer and damped them in the fall. Dredging may also have influenced tidal propagation in the tidal-fluvial reach. Aside from these points, little is known about the changes to the fluvial tidal regime over time or its effects on fish movement, mainstem spawning, and habitat availability. The physical aspects of these changes could, however, be quantified through analyses of historical data and numerical modeling.

Estuarine Sediment Dynamics

The estuary and its food web are strongly affected by sediment input, and these effects occur on several levels. First, continual sediment supply is needed to counter erosion of marshes and sea level rise (~1 mm year^{-1} in the estuary). Changes to the quantity and types of sediment input to the estuary over time have had effects on wetlands that have not been investigated.

Second, the organic component of the sediment supply is a vital source of nutrition to the estuarine turbidity maximum (Sherwood et al. 1990; Simenstad et al. 1990, 1992). The estuarine turbidity maximum food web is based on microbial processing of fluvial organic detritus. Much of this organic matter now stems from phytoplankton production in the reservoirs, whereas it previously contained a much higher percentage of material stemming from flood plain inundation and estuarine marshes. These changes may have affected the food supply for juvenile salmonids, but changes have not been quantified.

Third, decreased turbidities during the freshet season, combined with increased salinity intrusion and the presence of artificial sand islands (e.g., Rice Island) may have increased avian predation on juvenile salmonids. Finally, the reduction in sediment transport to the estuary has affected navigation by reducing the amount of sand that must be dredged from estuarine channels. Of all the factors mentioned in this section, changes to the sedimentary regime are the least understood. Understanding the effects on juvenile salmonids of altering the sediment dynamics of the system will require physical/chemical, geological, and biological observations, and perhaps numerical sediment transport modeling.

Effects of Future Climate Change

Human intervention in the flow cycle has had a larger effect on Columbia River hydrology than climate variations over the last 140 years. Moreover, the projected near-term effects of climate changes and climate fluctuations are not large enough to rival the impacts of human alterations to the flow cycle. As Hamlet and Lettenmaier (1999) point out, however, climate change may exacerbate conflicts over water supply during the critical spring freshet period, by increasing demand and decreasing natural flows at this time. Still, climate variations have also played a substantial role, so it is prudent to consider what changes may occur in the coming decades as the result of climate changes and fluctuations.

Changes in the PDO could have an important impact on future patterns of flow and sediment discharge in the Columbia River Basin. It is widely believed that the PDO cycle changed back to a cold phase between 1996 and 1998. If the past century is a guide, then this cold phase could last about 30 years. Another important factor in the PDO cycle is the synergy between the PDO and ENSO cycles. La Niña winters during the cold-PDO phase tend to be unusually severe (e.g., 1997 and 1999), while the effects of El Niño are muted. It is possible, however, that global warming has accelerated climate oscillations such that the duration of the cold phase may be less than 30 years, or the relationship between the PDO and ENSO cycles may change.

In this regard, 2000 was unusually dry and warm in the Pacific Northwest, despite being a La Niña winter. It was more typical of the years during the last PDO warm phase from 1977-1995. Although some relatively mild years (e.g., 1973) also occurred during the last cold phase, history suggests that the next several decades may be a period of unusually high flow and sediment discharge. While this may ease some of the conflict over water allocation, it will likely increase the need for dredging the Columbia River navigation channel, with all the impacts attendant to dredging and dredged material disposal.

Climate projections predict gradual regional warming, possibly accompanied by higher precipitation, especially in winter (Hamlet and Lettenmeir 1999). Just as the ratio of Columbia River winter to spring flows is naturally higher than that in the Fraser River because of the Columbia's more southerly position, a warmer climate will increase flows in winter and decrease peak and average spring freshet flows. Of the three spring freshet styles, flow regulation and diversion has greatly decreased flow volumes associated with the two that depend on an exceptional winter snow pack. Climate change will likely decrease (and may already have decreased) the probability of a 1948-style freshet caused by heavy spring precipitation on a late-arriving snowpack, because temperatures will be too high to allow significant snow accumulation in April and early May.

The frequency of major winter freshets (rain-on-snow events) in the interior sub-basin will likely increase unless the warming is sufficient to totally eliminate the low-elevation snow pack. The frequency of major western sub-basin freshets will likely

decrease even if rainfall increases, because low-elevation snow accumulation west of the Cascades will be decreased. An increase in rain-on-snow events in the interior sub-basin would likely increase the supply of fine sediment to the river and estuary. The effects on sediment supply in the western sub-basin are unclear. Even though very large flood events may occur less frequently, moderate flood events may occur more often.

Unresolved Issues

The results presented here represent a preliminary summary of a large, inadequately explored subject, namely downstream effects of human alterations and climate oscillations on the hydrology and sediment transport of the Columbia River Basin. As noted previously, changes to the river are being brought into focus, but effects on the estuary, and especially on the Columbia River plume (an extension of the estuary onto the continental shelf) are not well understood.

Specific issues related to the river and estuary that remain to be resolved include the following:

1) We are unable to determine historical changes in fine sediment supply to the system based on the historical sediment transport record, because fine sediment supply is affected by land use, and USGS observations do not extend far enough into the past. A concerted effort is required to assemble records from diverse agencies, and to construct a basin sediment supply model that can be used to investigate the effects of climate change, agriculture, silviculture, and urban development. Most important, systematic, long-term observations are needed at key points throughout the basin.

2) Historical reconstruction of sediment transport suggests that flow regulation has reduced sediment supply. It is unclear where this material is being retained or accumulated. There are three obvious possibilities: retention in tributaries (perhaps in small impoundments), retention behind mainstem dams, and retention along river banks and on the bed throughout the system. In the latter case, there would be no obvious area of sedimentation but rather a general lack of sediment movement.

3) The Willamette River and other western sub-basin tributaries have been highly altered, with extensive flow regulation, flow diversion, channelization, and alteration of tributary basins. We understand very little (relative to the interior sub-basin) of the effects of these alterations, which, along with climate change, have greatly influenced salmonids. These should be investigated via data collection, data analyses, and hydrological modeling.

4) Estuary tributaries below Beaver have also been highly altered, with major effects on salmonids, but here the data sources are more limited. Hydrological modeling and new observations would likely need to play a larger role in this case.

5) Historical records should be used to investigate the effects of flow regulation, water withdrawal, and climate on interior sub-basin flows and sediment input. In particular, USGS and Canadian government records should be used to understand alterations to the Snake River and to the Canadian part of the basin, the northern and southern extremes of the entire Columbia Basin.

  The Canadian sub-basin in particular has supplied a large part of the flow and perhaps much of the sediment during historical flood events. The effects of glacial melt on 19th-century river flow should be determined from analyses of flow records and the geological literature.

6) Historical changes in mainstem and tributary shallow water and floodplain habitats (caused by diking, filling, dredging, and dredged material disposal) should be documented, because they interact with hydrological alterations and have had major effects on salmonids. Habitat opportunity for salmon is a function of both river elevation (set by tides and river flow) and habitat structure. As noted in Chapter 4, habitat opportunity has been greatly changed, although the changes are poorly documented or understood.

7) Flow regulation and navigational development have had major effects on estuary habitats. Salinity and current data for 1933 to date and suspended sediment data from the 1960s to date should be analyzed and numerical models employed to understand changes in the estuarine salinity intrusion and particle trapping regimes. These physical changes can then be interpreted in terms of their effects on estuarine food web and salmonids. These efforts will likely require new observations, both for understanding processes and verifying numerical models.

8) The effects of hydropower regulation on mainstem tides and salmon spawning habitats need to be understood. This will require observations, data analyses, and numerical and theoretical models.

9) The frequency and magnitude of intense precipitation is generally on a scale with average precipitation. Intense precipitation events are likely responsible for much of the sediment supply to the system, especially during rain-on-snow events. Historical records should be employed to understand changes in precipitation patterns as a function of season and sub-basin.

10) The structure and function of crucial estuarine environments is strongly influenced by river flow and sediment supply. The effects of these changes on the estuarine turbidity maximum and on the structure of tidal flats and tidal marshes should be determined. Also, we need to determine how estuarine turbidity maximum physical and biological processes respond to changes in river flow and sediment supply.

11) The paleo-history of Columbia River flow and sediment supply, and effects thereof on salmonids, are not well defined. Also, the effects on physical and biological processes of catastrophic events need to be understood; these include:

   a) The Bridge of the Gods (>5,000 YBP) landslide.
   b) Major subduction earthquakes (e.g., those occurring in 1700 and at about 1,100 YBP).
   c) Volcanic activity and eruptions, several of which have occurred since 1800.
   d) Major floods with recurrence intervals at more than 100 years.

Conclusions

Human and Climate Influences on Flow and Sediment Transport

Columbia River mainstem flow and sediment transport affect salmonids in numerous ways, direct and indirect. Major changes over the last 120 years in Columbia River hydrological processes have resulted primarily from human alteration to the system and secondarily from climate processes.

Large-Scale Geography

The Columbia River has the largest flow (about 7,300 m^3s^{-1}) of any river on the Pacific coast of North America. Its annual average sediment discharge (ca. 10 x 10^6 t year^{-1}) is not unusually large, and is exceeded by several other western rivers. For hydrological purposes, the Columbia River Basin can be divided into western and interior sub-basins by the Cascade Mountains. The interior sub-basin (with 92% of the surface area and three-quarters of the flow) is, aside from its Canadian part, relatively arid. Almost the entire interior sub-basin flows pass the gauge at The Dalles, which has the longest daily flow record on the West Coast (1878-present). The western sub-basin contains only 8% of the area of the entire Columbia River Basin, but contributes about one-quarter of the flow. The Willamette River is typical of the western sub-basin; the flow record at Albany extends from 1892 to date.

SARE draft: Hydrological Conditions

Climate Change

Climate and flow conditions during the last half of the 19th century reflected the end of the "Little Ice Age" from about 1400-1850. This period was significantly cooler and wetter than present conditions. For example, 10 of the 14 strongest known freshets in the system occurred between 1849 and 1900, even after human manipulation of the flow is accounted for.

Climate Cycles

Cyclical climate phenomena exert a strong influence on Columbia River hydrology. Although the history of climate fluctuations in the region during the 19th century is unclear, effects of two cyclical processes were prominent throughout the 20th century:

1) The Pacific Decadal Oscillation (PDO) has a cycle that lasts 40-60 years and has likely been active for at least 300 years. Cold-PDO phases (e.g., 1945-1976) are generally associated with high river-flows and are favorable for salmonid production in the Pacific Northwest; warm phases (e.g., 1977 to 1995) are characterized by low river-flows and are less favorable for salmonid production. A new cold phase may have begun about 1996.

2) Indices of the El Niño-Southern Oscillation (ENSO; typically 3-7 years in duration) are also correlated with Columbia River flow. ENSO cycles affect survival of salmonids in the fluvial, estuarine, and ocean environments. Because strong El Niño or La Niña events typically last only 1-2 years, definition of ENSO impacts on salmonids is, however, less clear-cut than is the case with PDO impacts.

Pacific Decadal/El Niño Southern Oscillation Interaction

The PDO and ENSO cycles interact such that El Niño years are most intense during the warm-PDO phase and La Niña years during the cold-PDO phase. The average annual Columbia River flow at The Dalles is 111% of normal during cold-PDO'La Niña years, whereas it is only 85% during warm-PDO/El Niño years. The corresponding figures for the Willamette River are 119 and 81%.

Climate Effects on Sediment

Flow fluctuations are amplified by fluvial sediment transport, because sediment transport varies more than linearly with flow. Total sediment load during cold-PDO/La Niña years is more than 200% of that during warm-PDO/El Niño years in both the Columbia (at Vancouver) and the Willamette Rivers. Climate effects on sand transport are even stronger than those on total load.

Latitudinal Position

The Columbia Basin's climate response is conditioned by its position within a latitudinal band of strong response to both the ENSO and PDO cycles. The flow per unit area is much larger in the western than in the interior sub-basin, and latitudinal differences in the timing of snowmelt influence spring freshet properties. Still, there are only modest variations across the basin in response to ENSO or PDO forcing.

Annual Average Flow at The Dalles

Changes in annual average flow are an important integral measure of system alteration. The mean annual average flow of the Columbia River at The Dalles has decreased about 16.9% from 6,320 m^3s^{-1} (1879-1899 estimated natural or virgin flow) to 5,250 m^3s^{-1} (1970-1999 observed flow). We estimate that a 9% decrease is due to climate change, and ~7.4% is due to irrigation depletion.

Spring Freshet Properties

Spring freshet timing, strength,and duration are important to downstream migrant juvenile salmon. Spring-freshet properties have been much more highly altered than the mean flow. The average natural or virgin flow for the spring-freshet season (May-July) was ~13,600 m^3s^{-1} before 1900. This has decreased by ~5,870 m^3s^{-1} (43%) to 7,740 m^3s^{-1}, with most of this reduction (26.5%) due to flow regulation, 11% due to irrigation depletion, and 5.6% due to climate change. Thus, freshet-season flow at The Dalles is now only 148% of the present (reduced) mean flow, while it was 215% of the higher 19th-century flow. Flow regulation and the annual irrigation cycle have also increased fall and winter flows, the latter because of pre-release of water before the freshet.

Maximum Daily Flow at The Dalles

The observed maximum daily spring freshet flow has been reduced slightly more than freshet season flow, from 19,300 m^3s^{-1} (1858-1999) to 10,870 m^3s^{-1} (1970-1999), a decrease of 44%. This is a change from 305 to 207% of the mean flow.

Spring Freshet Timing at The Dalles

The timing of the maximum spring freshet flow also changed. Maximum daily spring freshet flow now typically occurs at about water-year Day 242 (May 29), whereas maximum flow occurred in the 19th century at about water-year Day 256 (June 12), a shift of about two weeks.

Willamette River Hydrology

Changes in the western sub-basin have been similar to those in the interior sub-basin, but are less well documented. The observed annual average Willamette River flow at Albany has decreased from 462 m^3s^{-1} for 1893-1900 to 394 m^3s^{-1} for 1970-1999, or 14.8%. Late summer and fall (August to December) flows have been augmented, whereas, average monthly flows during the January to July periods have decreased.

Columbia River Flow at the Mouth

The long-term average flow at the mouth of the Columbia River is 7,300 m^3s^{-1} (1892-1999). The value of the Columbia River flow at the mouth prior to 1900 was ~8,530 m^3s^{-1} and has decreased to ~7,080 m^3s^{-1} (1970-1999).

Changes in Sediment Transport

Sediment transport is a vital system characteristic for salmonids. Hindcasts from limited data collected during the 1960s suggest that the annual average sediment transport from the interior sub-basin has decreased from about 21 x 10^6 t (1858-1878) to ~8 x 10^6 t (1970-1999), a reduction of ~60%. We estimate that historical sand transport of over 10 x 10^6 t for 1858-1899 has decreased to 3.2 x 10^6 t, a reduction of ~70%. Most of the reduction in interior sub-basin sediment transport is related to the dam system, especially its reduction of spring freshet flow. In the Willamette River, historical sediment transport for 1893-1903 was approximately 2.4 x 10^6 t, compared with only 1.5 x 10^6 t for 1970-1999, a reduction of ~35%.

Disturbance Frequency

The frequency and magnitude of disturbance to the river system is important to salmonids. The historical bankfull flow level was ~18,000 m^3s^{-1} for the main stem below Vancouver. Modern bankfull level is set by the standard project flood level of ~24,000 m^3s^{-1} for the lower river. Some overbank flow occurred in many years before 1900. Flow regulation and water withdrawal have made overbank flow (above 24,000 m^3s^{-1}) rare, with significant events occurring only five times since 1948. Climate is a secondary factor with regard to the incidence of overbank flow. Overbank flow is now rare even during cold-PDO phases, and it was totally absent during the last PDO warm phase (1977-1995).

Changes in the River Flow Frequency Distribution

Low-frequency flow variations with periods between ~2 years and 6 months have been suppressed by the dam system, whereas high frequency variations associated with power peaking have been greatly augmented. The daily power peaking cycle also perturbs the diurnal (daily) tidal signal in the river.

Spring Freshet Styles

The flow cycle is different each year, but there are three recurring patterns of spring freshets: a) large winter snow pack without exceptional spring rain, b) normal winter snow pack with very high spring rainfall, and c) large winter snow pack combined with very high spring rainfall. The largest known freshet (1894) was of Type c), and the second largest (1948) was of Type b).

Winter Freshet Styles

There are also three types of winter freshets, based on the source of the flow: a) western sub-basin only, b) interior plus western sub-basin, and c) interior sub-basin only. All winter freshets are generated by rain-on-snow events, and the largest known freshets (e.g., 1861, 1881, and 1892) involved both sub-basins. The Canadian portion of the interior sub-basin is not usually affected by these floods.

Downstream Effects of Hydrological Alterations

Changes in Columbia River flow and sediment transport have exerted an important influence on the estuary, but these changes are not well understood. Effects of these hydrological changes on the Columbia River buoyant plume in the coastal ocean are almost totally unknown. The following downstream effects of hydrological change should be considered by future studies: estuarine salinity intrusion and salinity stratification, habitat availability, the fluvial tidal regime, sediment dynamics, and Columbia River plume area volume, turbidity, and seasonality.

Effects of Future Climate Change

Although climate effects on hydrology have been and will likely remain smaller than those of human manipulation, it is still vital to consider how climate will constrain future management options in the Columbia Basin, including efforts to restore depleted salmon populations. Climate projections suggest gradual regional warming, possibly accompanied by higher precipitation, especially in winter. This would likely lead to increased incidence of winter freshets and lower natural spring freshet flows.

These changes would exacerbate conflicts over water supply during the critical spring freshet period, by increasing demand and decreasing natural flows. However, if the climate shifted back to a cold-PDO regime, as it did around 1996, the impact of longer-term climate change could be delayed 20-30 years.

Recommendations

This review has raised as many questions as it has answered. Future research is needed to resolve the following issues:

1) A basin sediment supply model is needed to investigate the effects of climate change, navigational development, agriculture, silviculture, and urban development on sediment transport. This will have to be supported by measurements at key points throughout the basin.

2) Flow regulation has apparently reduced mainstem sediment transport. The fate of the sediment not now being carried to the estuary should be determined.

3) The effects of human manipulation and climate on western sub-basin tributaries (including estuary tributaries) should be investigated via data analyses and hydrological modeling.

4) Changes in the hydrology of Snake River and Canadian portions of the basin, the northern and southern extremes of the system, should be analyzed, because of their importance to freshets.

5) Historical changes in mainstem and tributary shallow water and floodplain habitats (caused by diking, filling, dredging and dredged material disposal) should be documented.

6) Historical salinity and current data should be analyzed and numerical models employed to understand changes in the estuarine salinity intrusion, salinity stratification, and particle trapping regimes. The effects of hydrological change on the estuarine turbidity maximum and its ecosystem should be determined. These efforts will likely require new observations, both for understanding processes and verifying numerical models.

7) The effects of hydropower regulation on mainstem tides and spawning habitat need to be understood. This will require observations, data analyses, and numerical and theoretical models.

8) The paleo-history of Columbia River flow and sediment supply and its effects on salmonids should be investigated.

4. ESTUARINE HABITAT OPPORTUNITY

SARE draft: Habitat Opportunity

Introduction

Rationale for Modeling Approach to Evaluate Opportunity

An observation and forecasting system for the Columbia River estuary has been under development since 1996 (OGI 1997, Baptista et al. 1999). Conceived as a multipurpose infrastructure system for science and management, the Columbia River Estuary Forecasting System (CORIE) includes integrated modeling and observation components (Fig. 4.1) that now regularly generate a variety of products describing the physical environment of the Columbia River below Bonneville Dam.

Among the regular CORIE products are forecasts of depth-averaged circulation, made daily since 1997 (OGI 1997). At the core of the forecasts is a numerical model, which solves for mass and momentum conservation equations inside a predefined computational domain, given bathymetry and boundary forcings. Circulation is described in the form of water levels and velocities, in a computational grid that extends from Longview to the coastal ocean (Fig. 4.2a). Circulation forecasts are generated daily, with predictions compared on-line against real-time observations from the CORIE observation network. This comparison allows a continued understanding of the capabilities and limitations of the model, and has over time led to progressively better predictions.

A complementary product, generated more sporadically, consists of month-long hindcasts of depth-averaged circulation. Simulations are in this case done retrospectively, and the computational grid is larger, extending from Bonneville Dam to the coastal ocean (Fig. 4.2b). Boundary conditions are imposed based on observations rather than predictions of the external forcings. Comparisons against observational data, when required, are done off-line. Prior to the beginning of this review, month-long hindcasts were available for 1997 and part of 1998.

The ability to represent water levels and velocities with good spatial resolution, for long periods of time and within reasonably controlled quality, opens intriguing opportunities to explore patterns and trends of physical behavior and estuarine habitat opportunity for juvenile salmon in the modern Columbia River system. In particular, it is possible to process the model-generated data to evaluate indices of physical performance of the estuary, which can then be used as context to interpret fisheries data.

The computation of these indices can be done flexibly in time and space, because model results are available at small intervals (15 minutes) and as a pseudo-continuum within the computational grid. Thus, indices can be conveniently analyzed for spatial patterns and seasonal and interannual trends and dependencies relative to external forcings such as river discharge (flow). Model simulations and calculation of associated indices can also be performed for predevelopment (historical) conditions and for future scenarios of management, thus providing the ability to understand and learn from historical conditions and to anticipate future change.

One goal of the present investigation is to explore the use of CORIE modeling products to characterize modern variability and historical trends in the physical habitat of the Columbia River. We focused on developing concepts and methods to utilize simulation databases to develop a practical, objective framework for analysis of the influence of estuarine physical habitat on salmon survival. Outcomes will need to be revised and extended in the future. In particular, there is an implicit understanding that
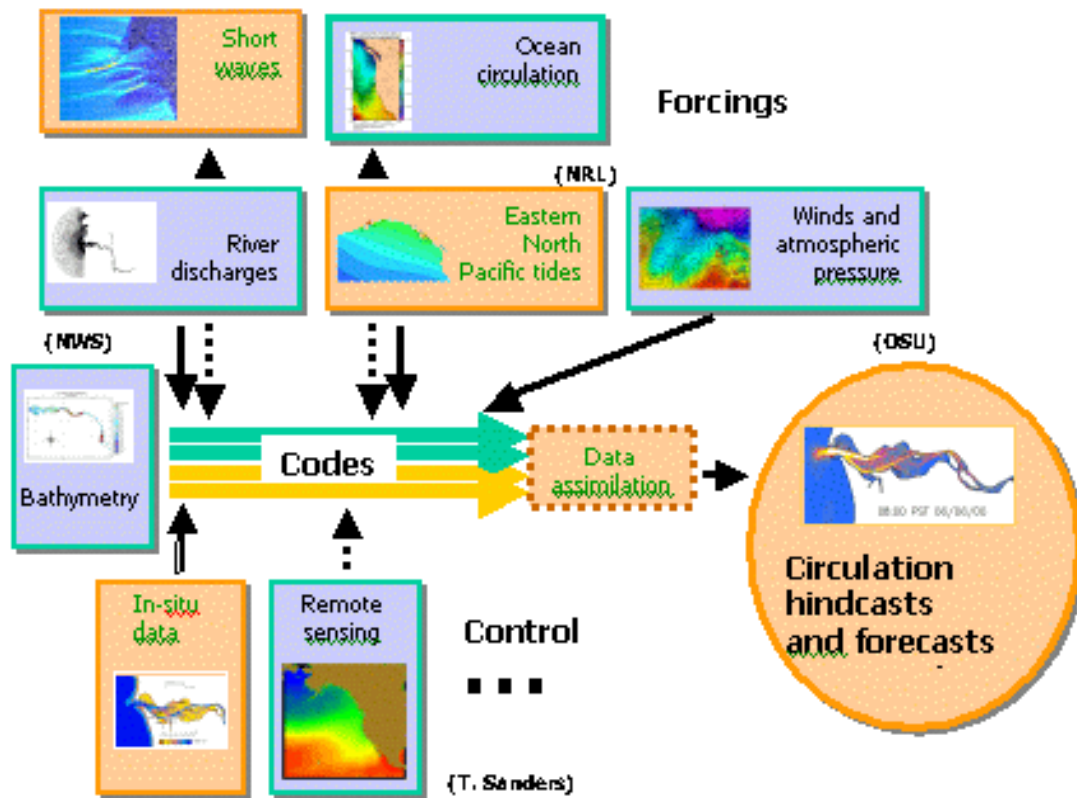
Figure 4.1. The CORIE modeling infrastructure integrates numerical models, supporting pre- and post-processing tools, and internal and external sources of data, towards the development of forecast and hindcast simulations that are progressively more detailed, reliable, and easier to communicate to diverse audiences.
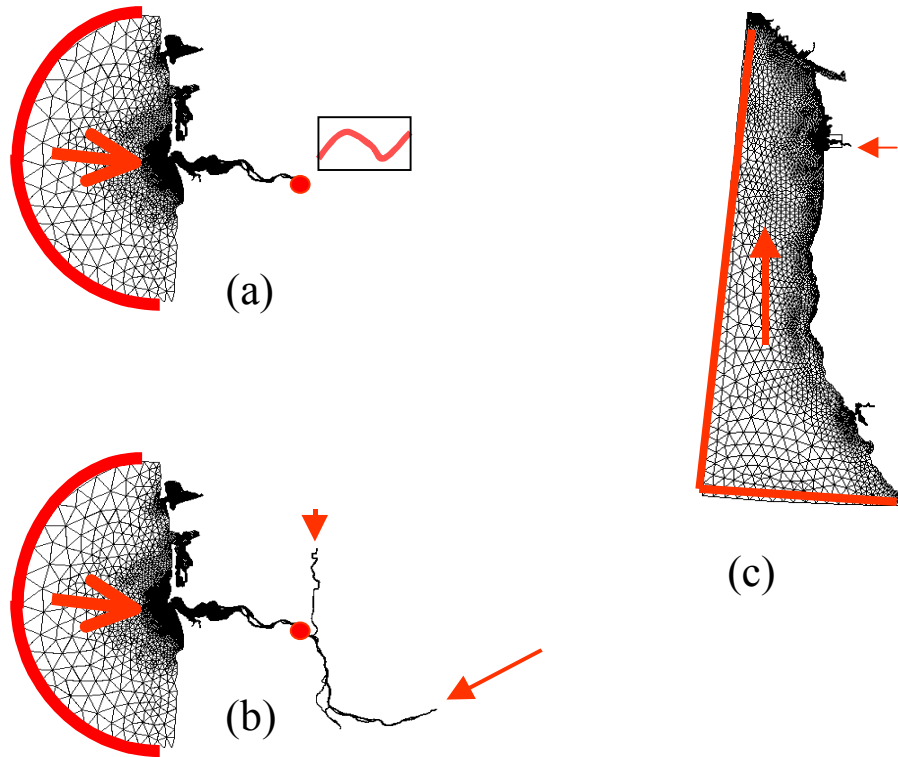
Figure 4.2. CORIE domains of simulation: (a) depth-averaged forecasts (since 1997); (b) depth-averaged hindcasts (since 1997); and (c) three-dimensional forecasts and hindcasts (since Fall 2000, experimental). Domain (b) is the basis for simulations in this report.

the robustness and extent of the circulation simulation database can and should be increased over time. Therefore, findings of this investigation should be considered as guiding hypotheses rather than established protocols.

One of the challenges faced in the investigation was the definition of indices that appropriately describe variability in physical habitat in ways that can be related to the interpretation of fisheries data. After several iterations, we converged on indices related to physical habitat opportunity, residual velocities, and hydrodynamic residence times. All indices were inherently defined as a function of space and time, but results were often integrated over predefined regions and periods to synthesize findings and facilitate analysis of seasonal and historical trends.

The concept of modeling indices of physical habitat opportunity is novel but provides a very natural link between estuarine physics and interpretation of ecological and fisheries data. The concept is simple, requiring only a binary decision on whether the physical habitat is or is not favorable to juvenile salmon with regard to the prevailing conditions of water velocity, water depth, or both. Specification of the criteria that define "favorable conditions" is more challenging. The rationale for this specification is discussed in the next section.

Residence times and residual velocities are conventional indices of physical estuarine behavior that reflect net transport. As defined in this investigation, they relate strictly to net hydrodynamic transport (i.e., they are not tied to any particular biological or ecological tracer, and thus do not reflect self-propelling motion or deposition/erosion processes). Each index integrated water motion over space or time. In the case of residence times, integration is over both space and time, along the path of a parcel of water as it leaves the estuary. In the case of residual velocities, integration is over a multiple of a tidal period, at a fixed position in space.

Establishing Criteria for Subyearling Salmon Physical Habitat Opportunity

Juvenile salmon respond to a variety of habitat characteristics that collectively affect their migration behavior through estuaries, including both abiotic conditions such as temperature, salinity, and turbidity and biotic conditions such as prey availability. The focus on subyearling, ocean-type species and life-history types, particularly in chinook salmon, allows the setting of more constrained parameters for model simulations because they tend to have more restricted habitat requirements than stream-type species and life-history type.

Depth--Subyearling salmon, migrating through estuaries as fry or fingerlings, behaviorally restrict their movements to shallow water until they reach larger sizes that may allow them to exploit deeper channel and open-water habitats and associated prey resources (Groot and Margolis 1991). Chum and chinook fry in particular prefer shallow-water areas; both species occupy tidal wetland sloughs and channels, mud and sand flats, or beaches at sizes ranging from 30-60 mm fork length (Healey 1982, 1991; Simenstad et al. 1982; Salo 1991). At sizes between 55-60 mm fork length, chum fry often move into deeper offshore waters (Bax et al. 1980, Simenstad and Salo 1982). Subyearling chinook may occupy estuarine marsh and other shallow-water habitats until above 100 mm fork length (Healey 1982, Levy and Northcote 1982). These and other investigations in estuarine habitats suggest that salmon fry and fingerlings often remain within water depths between about 10 cm and 2 m. While we acknowledge that there is considerable

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variability in fish movements and that salmon migrate outside this range, this depth window is used as one criterion for simulating estuarine habitat opportunity for subyearling, ocean-type chinook.

Velocity--The opportunity for salmon fry and fingerlings to access estuarine habitats may also be determined by their swimming performance and the energetic constraints of maintaining position against tidal or river currents. Therefore, velocity was defined as a second criterion for simulating habitat opportunity for salmon fry and subyearlings.

Various laboratory studies have measured the swimming performance of juvenile salmonids as a function of fish size (body length); duration of swimming activity, including "sustained" vs. "burst" speeds; and various environmental variables, including temperature and dissolved oxygen (e.g., Hoar and Randall 1978). Beamish (1978) reviewed swimming performance of fish from various laboratory studies, including sustained swimming speeds, defined as speeds that fish could maintain for long periods (> 200 minutes) without muscle fatigue. Davis et al. (1963) reported sustained swimming speeds of 23 to 67 cm s^{-1} for 81- to 126-mm chinook salmon at an acclimation temperature of 11.5°C. For somewhat smaller subyearling chinook (51-73 mm) acclimated at 15°C, maximum sustained swimming speeds ranged from 29 to 53 cm s^{-1}. Based on these results, 30 cm s^{-1} was chosen as a threshold velocity for modeling the availability of low-velocity rearing habitat for subyearling chinook within the Columbia River estuary. To assess model sensitivity to different assumptions of habitat suitability, habitat opportunity was evaluated using a 50 cm s^{-1} threshold velocity.

Simulation Scenarios, Methods, and Uncertainty

The two-dimensional circulation database used in the present investigation is summarized in Table 4.1. The database includes simulations for modern and predevelopment bathymetry and for modern and predevelopment river discharges. Simulations for the modern system cover 1997 and 1998, the first five months of 1999, and selected months in the spring of 1980. Simulations for the predevelopment system cover selected months in 1880, typically associated with high (May, July) or low (December) river discharges. The 1880 simulations were often conducted for two alternative bathymetries, as discussed later in this section. In some cases, 1880 bathymetry and 1997 river discharges were combined in an attempt to separate the effects of change in river discharge from those of change in bathymetry.

The 1997 and 1998 simulations were already available, but other simulations needed to be conducted as a part of the investigation. The process used in all simulations was similar, and involved the steps described below.

Choice of the Computational Domain

Both the modern and predevelopment systems were represented from Bonneville Dam to the coastal ocean (Fig. 4.2b). The extent to which shallow peripheral areas were incorporated in the computational domain for the modern and the predevelopment system was not fully consistent (see creation of the bathymetric database below).

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Table 4.1. Summary of two-dimensional simulation database for bathymetric and velocity analyses. Months for which simulations are available are shaded..

1880	1880[a]	1880[b]	1980	1997	1998	1999
				January	January	January
				February	February	February
				March	March	March
			April	April	April	April
May	May	May	May	May	May	May
				June	June	
July		July		July	July	
				August	August	
				September	September	
				October	October	
				November	November	
December	December			December	December	

[a] Simulations with predevelopment bathymetry, modified as described in Appendix.

[b] Simulations with predevelopment bathymetry, but with 1997 river discharges.

Creation of the Bathymetric Database

Generating the bathymetric database for the computational domain is a resource- and time-consuming task. We realized early in the project that resources were insufficient to generate two bathymetric databases. Therefore the existing CORIE modern bathymetry was used, concentrating on the careful reconstruction of predevelopment bathymetry. While this decision was critically important to make this investigation feasible, it carried costs in cross-consistency of assumptions.

The modern CORIE bathymetry (Fig. 4.3a) was generated in late 1996, at a time when modeling emphasized the circulation dynamics of the deeper regions of the estuary (e.g., navigation and north channels). The bathymetric base for the entire estuary utilizes NOAA survey results from the period in 1958, but is overridden in the channel and vicinity by the 1996 U.S. Army Corps of Engineers surveys. While shallow areas are represented in this base map, assumptions for regions without survey data (in particular, island formations, such as in Cathlamet Bay) tend to overestimate depth.

The GIS-based process followed the generation of the predevelopment bathymetry (Fig. 4.3b). Careful analysis of historical bathymetry relied on informed assumptions where survey data were unavailable. Areas of uncertainty typically focused around island formations. To test the sensitivity of the characterization of physical estuarine habitat to our bathymetric assumptions, a second predevelopment bathymetric coverage (Fig. 4.4b) was created that likely overestimated water depth around island formations. This overestimation roughly approximates that of the modern CORIE bathymetry and allows testing of the sensitivity of the model to alternative assumptions about historical depths.

Creation of a Computational Grid

The hydrodynamic model used in this study (see below) solves the conventional shallow water equations (partial differential equations reflecting conservation of mass and momentum) in an unstructured computational grid formed by triangular elements (Fig. 4.2). Generation of this grid consists of positioning the computational nodes (the vertices of the triangles) over the domain in ways that reflect the desired level of resolution (which typically varies from region to region of the domain). Higher resolution is sought in areas typically representing high gradients in bathymetry or water circulation.

Specification of Boundary Conditions

Prior to any simulation, external forcings need to be specified at the boundaries of the computational domain. The barotropic circulation in the Columbia River estuary is primarily controlled by two external forcings: ocean tides and river discharges.

Tides were specified by harmonic synthesis, for the period of simulation, of tidal constituents derived from the Eastern North Pacific tidal model of Myers and Baptista (2000). David Jay and co-workers provided representative river discharges at Bonneville Dam, Willamette River, and Cowlitz River (see Chapter 3).

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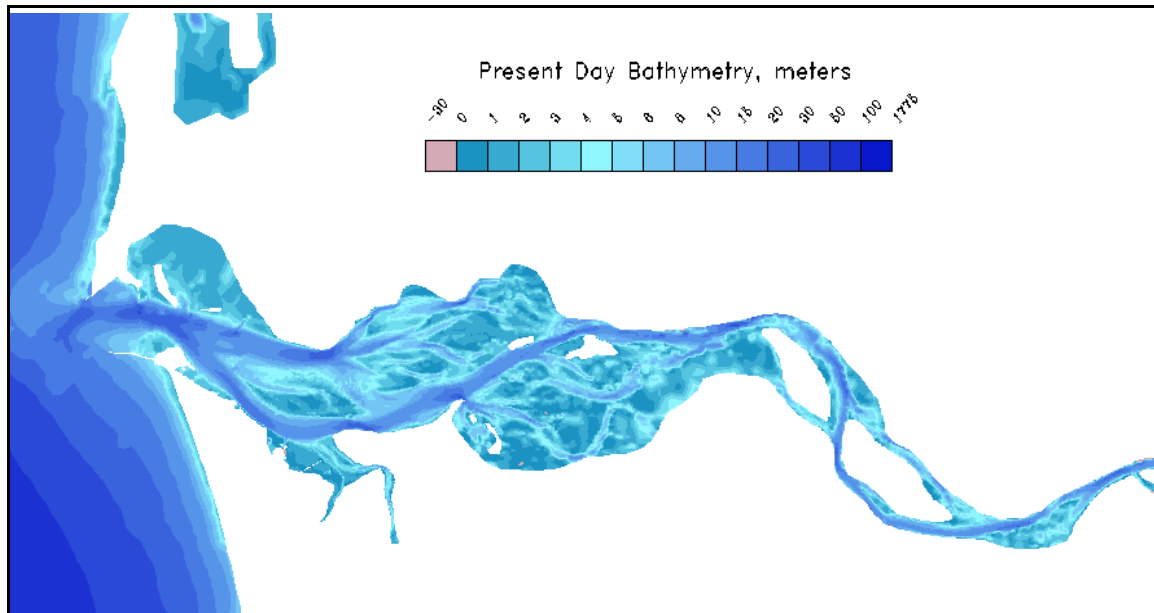
Figure 4.3a. Model bathymetry for the modern and pre-development systems was derived at different times, with different modeling purposes and support technologies. Modern model bathymetry predates this study, without focus on detailed representation of very shallow areas (e.g., in Cathlamet Bay), which may be deeper than in reality. Outside the navigation channel area of influence (where there are modern Corps of Engineers surveys), this bathymetry is based on surveys from the late 1950s.
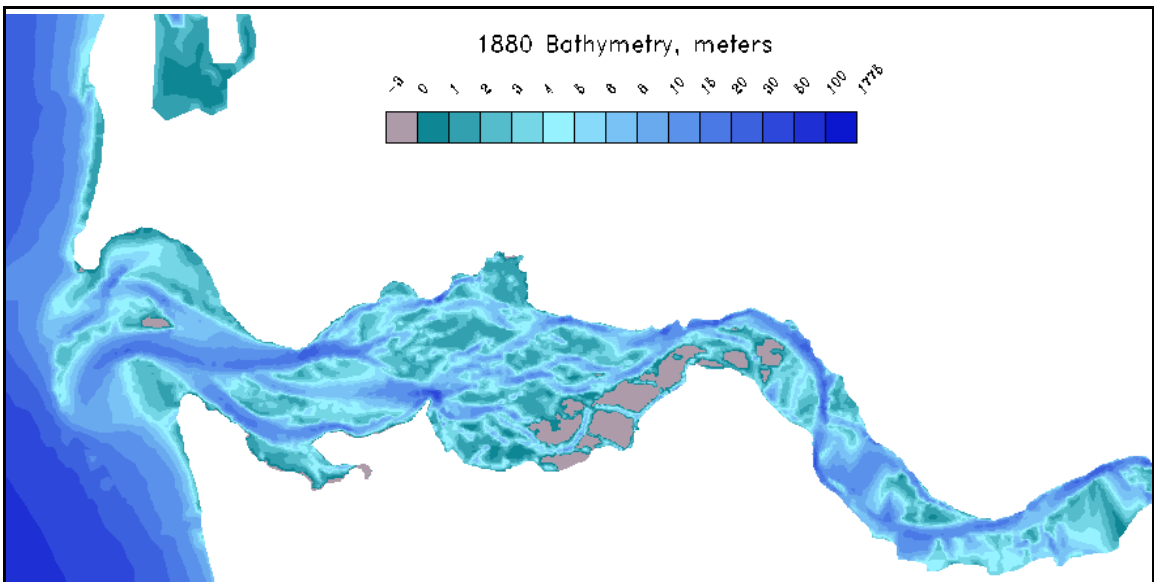
Figure 4.3b. Pre-development bathymetry is based on surveys from the 1870s and 1880s. While the density of the survey points is smaller, more sophisticated GIS techniques were used to render the bathymetry, and more care was used in representing shallow areas as accurately as allowed by survey data (see appendix).

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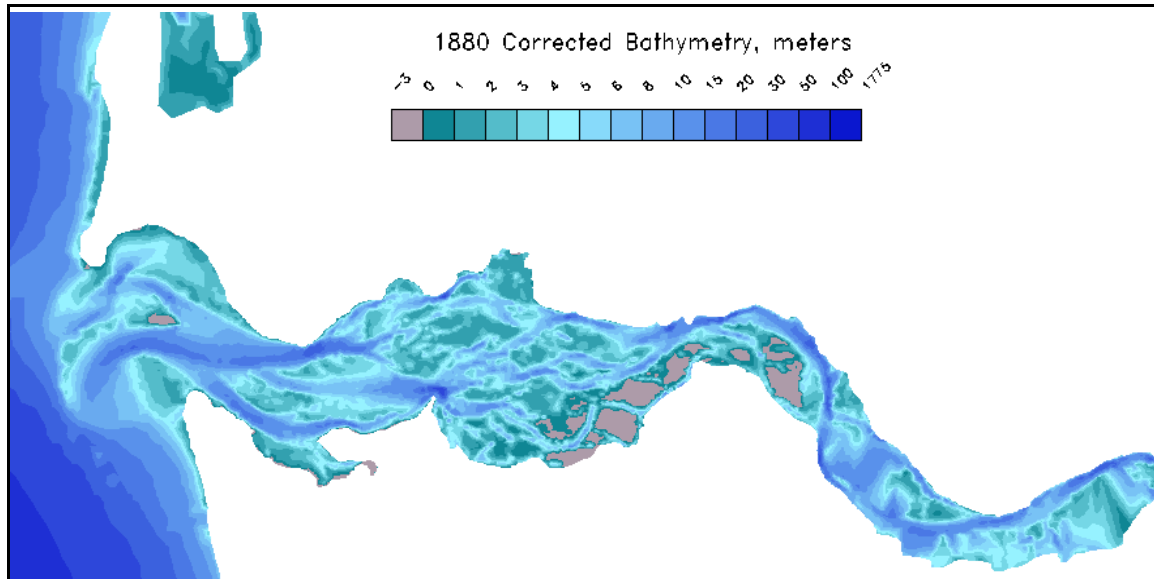
Figure 4.4a. Model bathymetry for the pre-development system, with controlled changes introduced to enable an analysis of the sensitivity of habitat opportunity to the uncertainties in bathymetry.
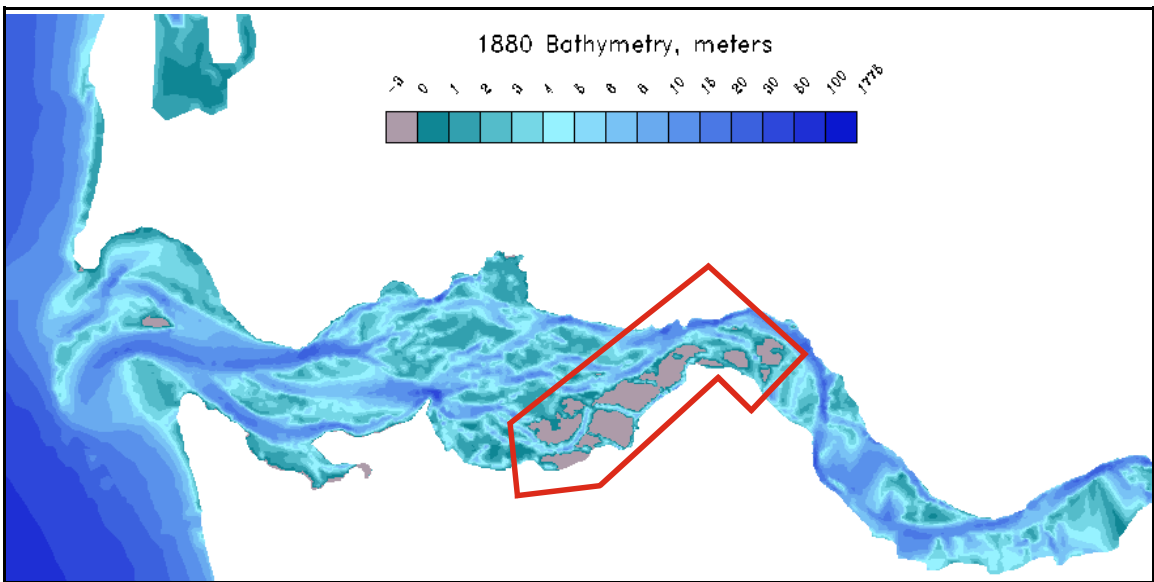
Figure 4.4b. Original pre-development bathymetry, for easy visual contrast. The polygon bounds the area affected by the changes, which tend to deepen the Cathlamat Bay area, and are described in detail in the appendix.

Simulation Model

Simulations were conducted with ADCIRC, a model developed at the U.S. Army Corps of Engineers Waterways Experimental Station (Luettich et al. 1991, Luettich and Westerink 1995). The two-dimensional version of the model was used here, with options enabled for treatment of wetting and drying. Calibration and validation of the model were conducted for the modern system (part of the CORIE modeling procedures). A carefully calibrated and verified estuarine model that properly reflects current operating conditions will presumably substantiate the model's characterization of the historical estuary, within the limits of uncertainty for bathymetry and external forcing.

Analysis of the data was consistent across simulations, and typically involved:

- Calculation of indices (residence times, residual velocities and habitat opportunity) at the nodes or elements of the computational grid, and typically as a function of time.

- Spatial mapping of indices, either for the entire domain or sub-regions.

- Integration of indices, across time and/or space, in the latter case over the entire domain or sub-regions.

- Correlation of integrated indices with river discharges at Bonneville Dam.

The process of data analysis was automated. Detailed results of the analyses are available on the internet (OGI 1999).

It is important to recognize that modeling, whether for modern or predevelopment conditions, has inherent errors and uncertainties. Identification and mitigation of these errors and uncertainties is challenging, especially for a complex system like the Columbia River. The CORIE infrastructure approaches this challenge with a long-term perspective. Each new application or research project contributes incrementally to extend modeling capabilities, database coverage, reliability, and awareness of modeling limitations.

This investigation focused on extending modeling capabilities (through the creation of a predevelopment bathymetry and through the systematic creation of indices of physical habitat opportunity and net hydrodynamic transport) and database coverage (through simulation of selected months in 1880, 1980, and 1999). Some modeling limitations were also identified, and will be discussed. However, it was beyond the scope of this investigation to systematically identify modeling uncertainty or to improve the inherent quality of the hydrodynamic simulations. Important goals of these simulations were to evaluate this new method for assessing estuarine habitat opportunity and to understand the relative sensitivities of the model to changes in physical variables, principally depth and river flow.

Results

Habitat Opportunity

For each of the three criteria identified, hours of habitat opportunity (defined as hours within a month period where the criterion is locally met) were computed for each node of the computational grid, for all available months in the simulation database, and then normalized to 720-hour months. Isolines of the resulting normalized habitat opportunity for the entire estuary were plotted for each (modern and predevelopment) month of the simulation database. An example of the isolines for May 1997 is shown in Figure 4.5. Isolines for other months can be seen at the web site of the Center for Coastal and Land-Margin Research (CCALMR; OGI 1999).

To facilitate the analysis, the estuary was also divided into six regions of distinct characteristics relative to topology, bathymetry, and distance to the ocean (Fig. 4.6a). Regions 2 and 6 represent, respectively, the lower and upper mainstem of the estuary, whereas Regions 1 and 3-5 represent the major peripheral bays: Baker Bay, Youngs Bay, Cathlamet Bay, and Grays Bay, respectively.

Within each region, integral indicators of habitat opportunity were computed as weighted averages over the appropriate portion of the computational domain. Isolines of habitat opportunity were drawn for each region and month. Figure 4.7 shows an example for Cathlamet Bay, in May 1997; additional periods and regions are available on the internet (OGI 1999). Differences of habitat opportunity were also computed relative to selected "reference months" (May 1997, July 1880, May 1880, and May 1880; see Table 4.1), and resulting isolines were drawn (e.g., Figure 4.8, with more extensive coverage available at the CCALMR web site; OGI 1999). The seasonal variation of integral indicators of habitat opportunity was also plotted (Figs. 4.9-4.12), as well as the relationship of these indicators to river discharge (Fig. 4.13-4.16) to compare the responses of different regions and of modern and predevelopment systems.

The results introduced above constitute a massive amount of information from simulations of habitat opportunity (for depth and velocity criteria), retention times, and residual velocities for various combinations of historical and modern bathymetry and river flow. The following sections, organized by criterion, synthesize, interpret, and discuss the implications of these results.

Velocity Criterion--Several distinct patterns and trends emerge in the characterization of habitat opportunity based on the velocity criterion. In particular, there is a strong correlation of habitat opportunity with river discharge, but this correlation is distinct for the various regions under consideration (Fig. 4.13) and for the modern (Fig. 4.13a) and predevelopment (Fig. 4.13b) systems

Habitat opportunity is highest in Youngs Bay (Region 3) and Baker Bay (Region 1), the two lateral bays closest to the ocean, and tends to decrease in an upstream direction. Habitat opportunity is high to moderate, clearly decreasing with increasing river discharge, in Cathlamet Bay (Region 4) and Grays Bay (Region 5), two lateral bays located farther upstream in the estuary. Habitat opportunity is moderate to essentially nil in the upper estuary (Region 6) and decreases sharply with river discharge. Habitat opportunity is low in the main stem of the lower estuary (Region 2), and insensitive to river discharge.

Figure 4.5. Isolines of estuarine habitat opportunity for May 1997, in hours normalized to a 30-day month, using respectively (a) depth criterion, (b) velocity criterion, and (c) combined criteria. The depth criterion is substantially more stringent than the velocity criterion, which leads to similarities in the patterns for the depth and combined criteria. Similar representations, for all months in the simulation database, can be found on the internet (OGI 1999).

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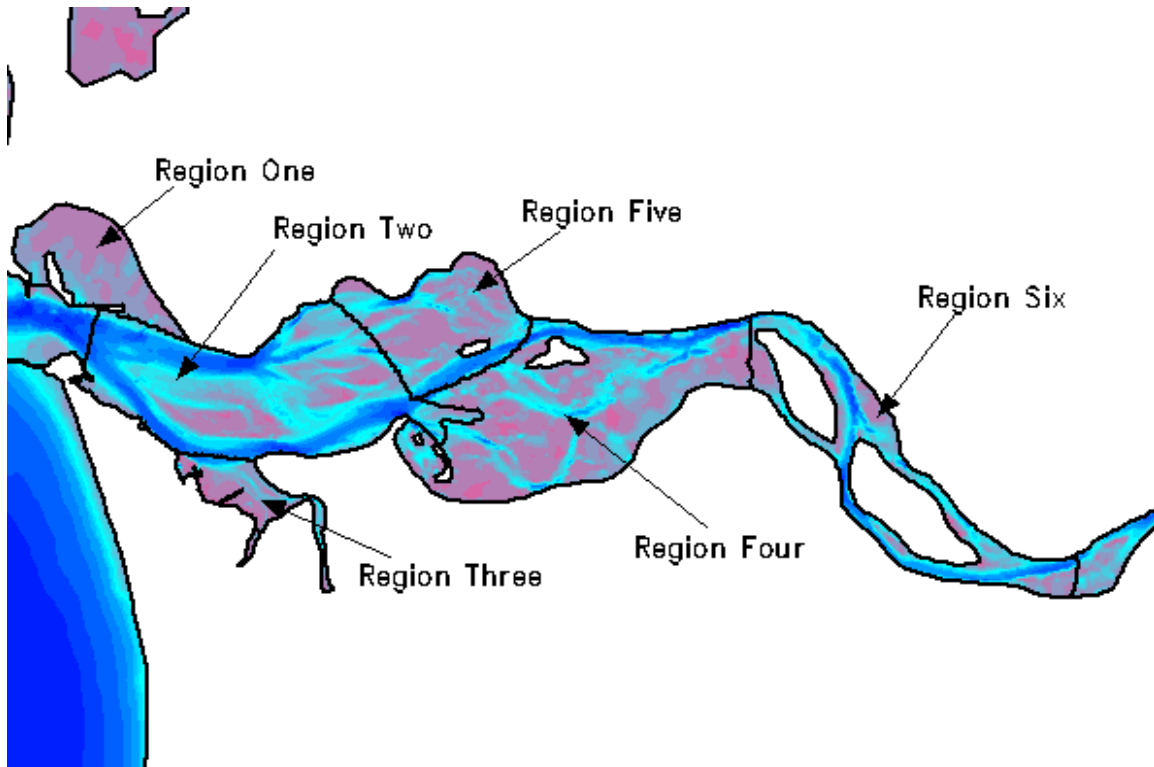
Figure 4.6a. Different environments in the estuary offer distinct habitat opportunity. In an attempt to capture differences in trends and patterns, the estuary was divided into the sub-regions shown, for rough consistency with a prior CREDDP study.
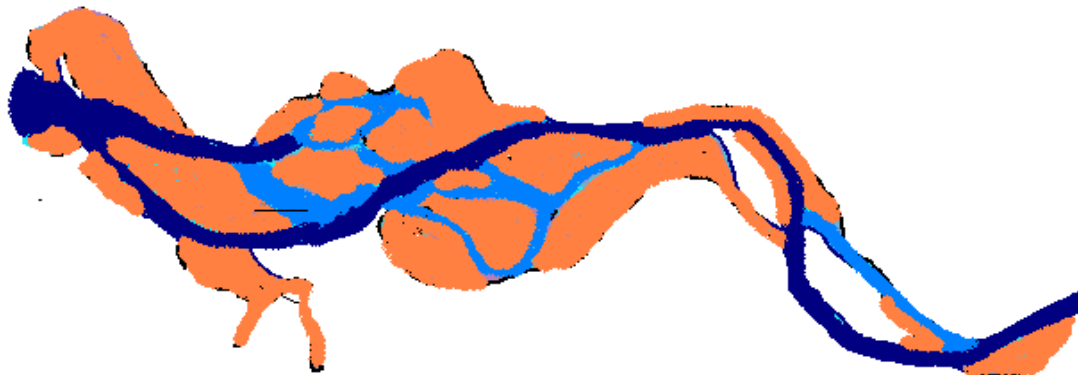
Figure 4.6b. An alternative concept, beyond the scope of this study but worth future exploration, is inspired in the analogy of a road system serving multiple neighborhoods. Sub-regions would include multi-hierarchy channels (darker areas) and the shallow regions (lighter area) bounded by them and land. Shallow regions could be analyzed individually or in groups, and channel hierarchy could be extended to any order consistent with the resolution of the circulation model. Objective criteria (e.g., based on bathymetry and connectivity) could be used to carve the domain into regions.
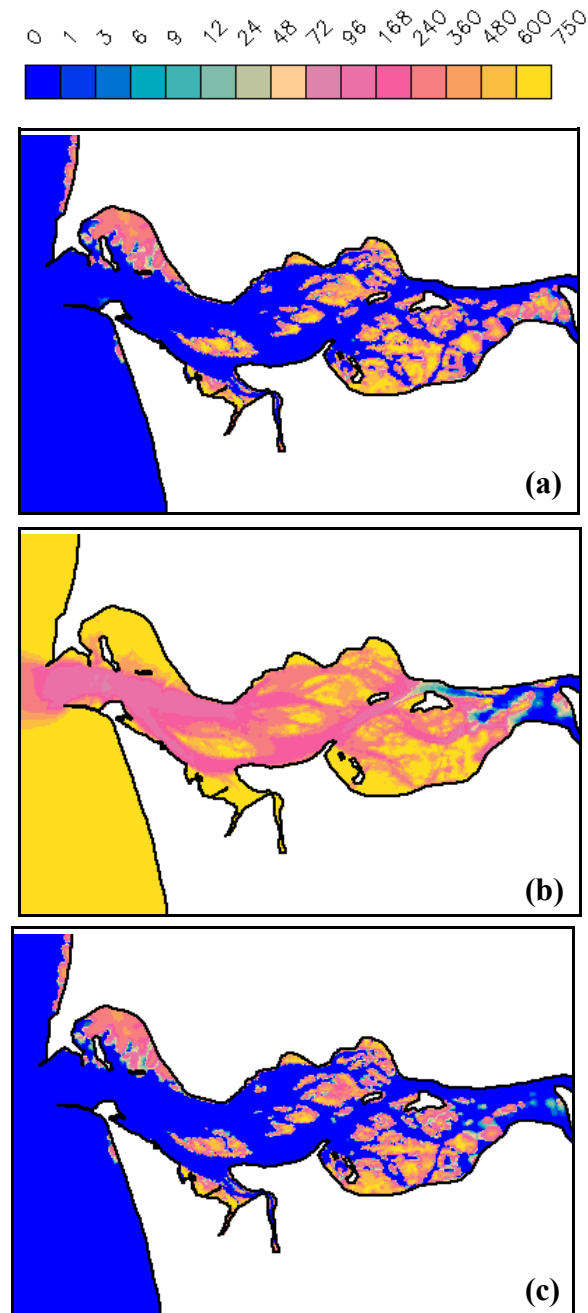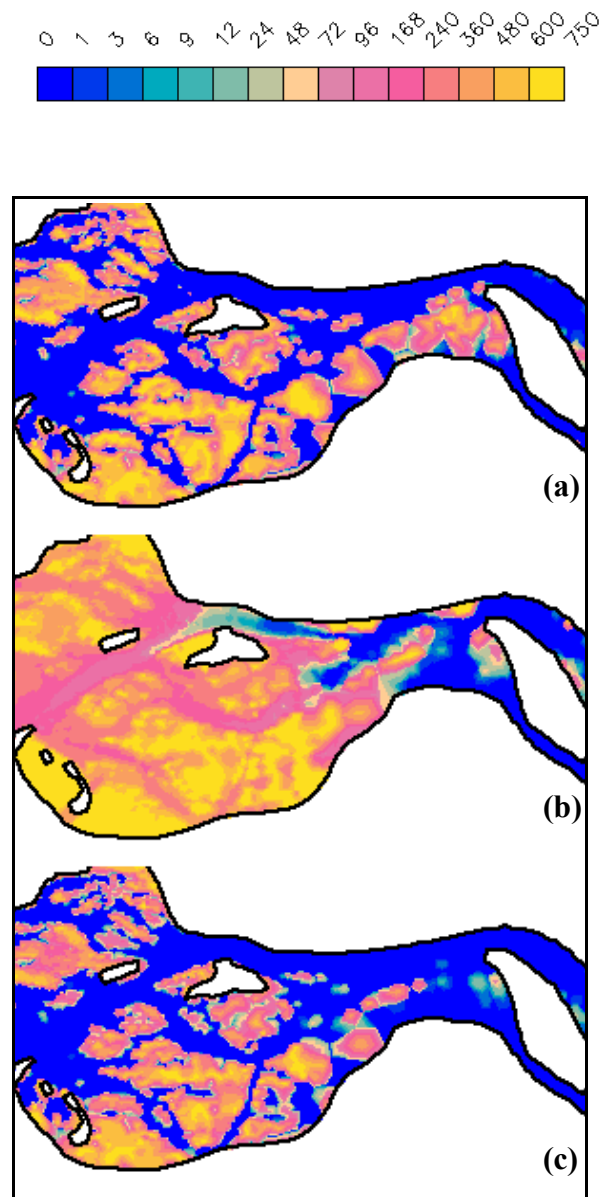
Figure 4.7. Isolines of habitat opportunity in Cathlamet Bay for May 1997, in hours normalized to a 30-day month, using respectively (a) depth criterion, (b) velocity criterion, and (c) combined criteria. Similar representations, for all months in the simulation database, and for all sub-regions, can be found on the internet (OGI 1999).
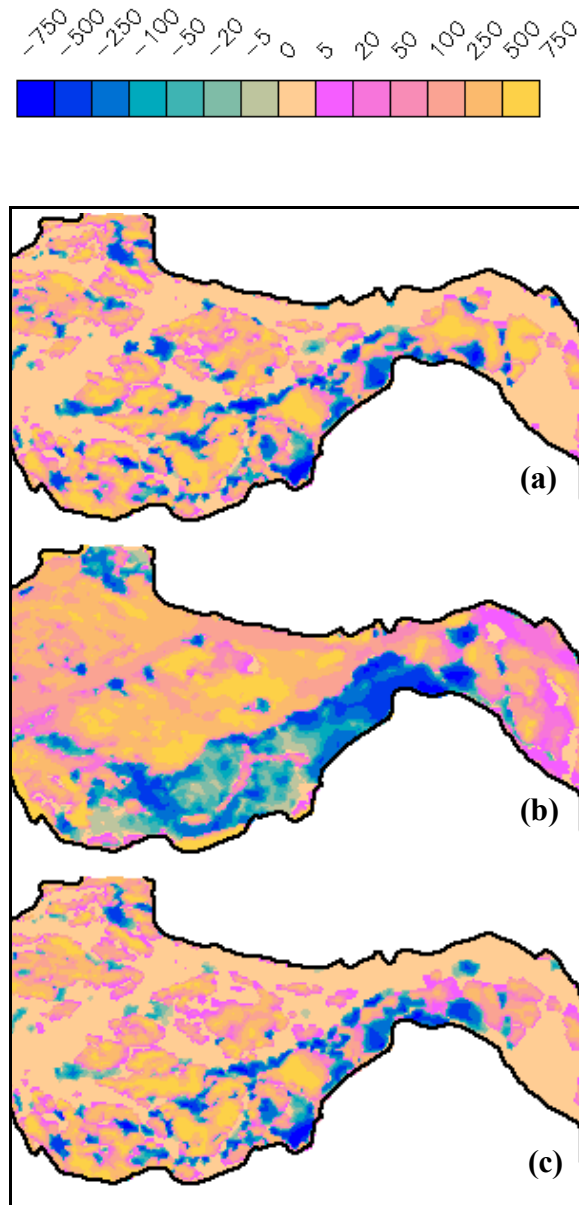
Figure 4.8. Isolines of difference of habitat opportunity in Cathlamet Bay (July minus May 1997), in hours normalized to a 30-day month, using respectively (a) depth criterion, (b) velocity criterion, and (c) combined criteria. Positive values (clearly dominant under any criteria) represent higher opportunity in July, which has lower river discharges. Similar representations for all months in the simulation database (relative to May 1997, May 1880, May 1880* or July 1880), and for all sub-regions, can be found on the internet (OGI 1999).

(a)

(b)
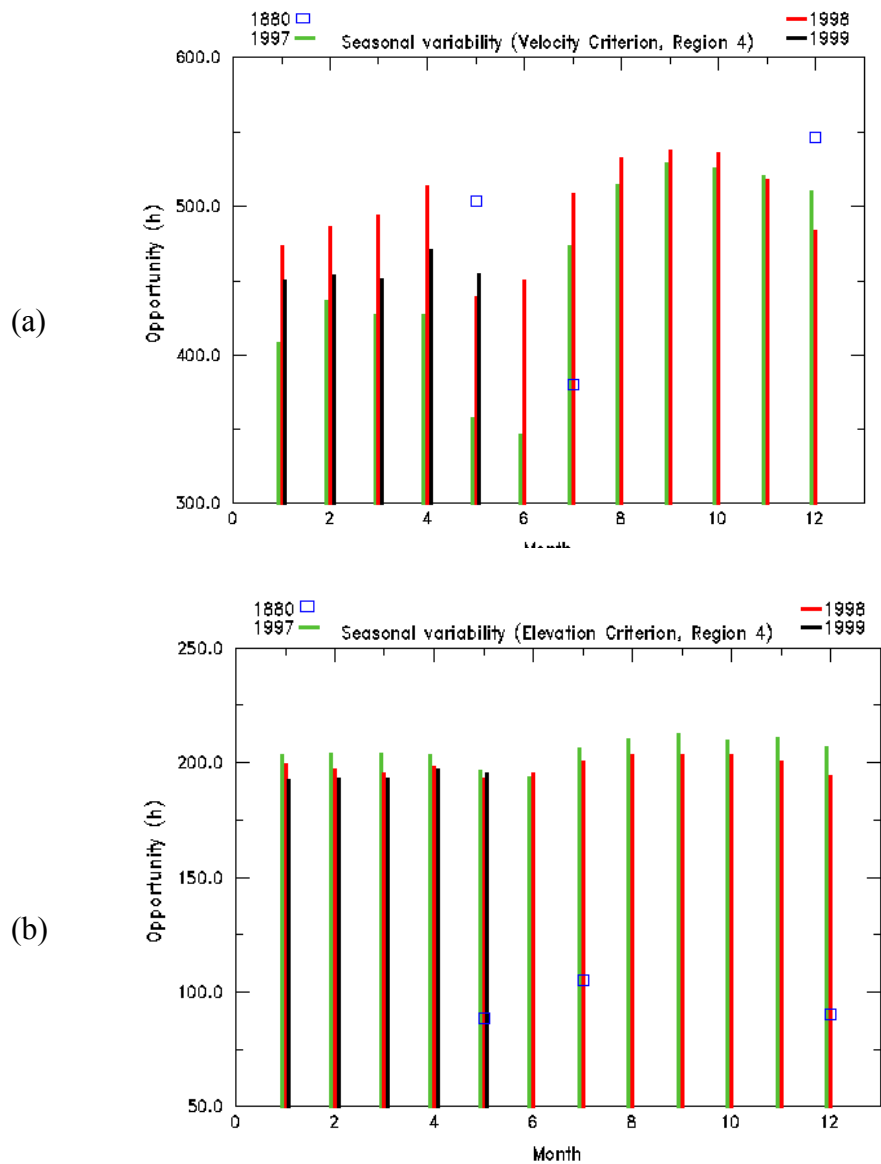
Figure 4.9. Seasonal variation of estuarine habitat opportunity in Cathlamet Bay, for (a) velocity criterion and (b) depth criterion. Habitat opportunity is shown in hours normalized to a 30-day month. Habitat opportunity based on the velocity criterion (but not on the depth criterion) shows marked minima during freshet season. Similar representations for all sub-regions and criteria can be found on the internet (OGI 1999).
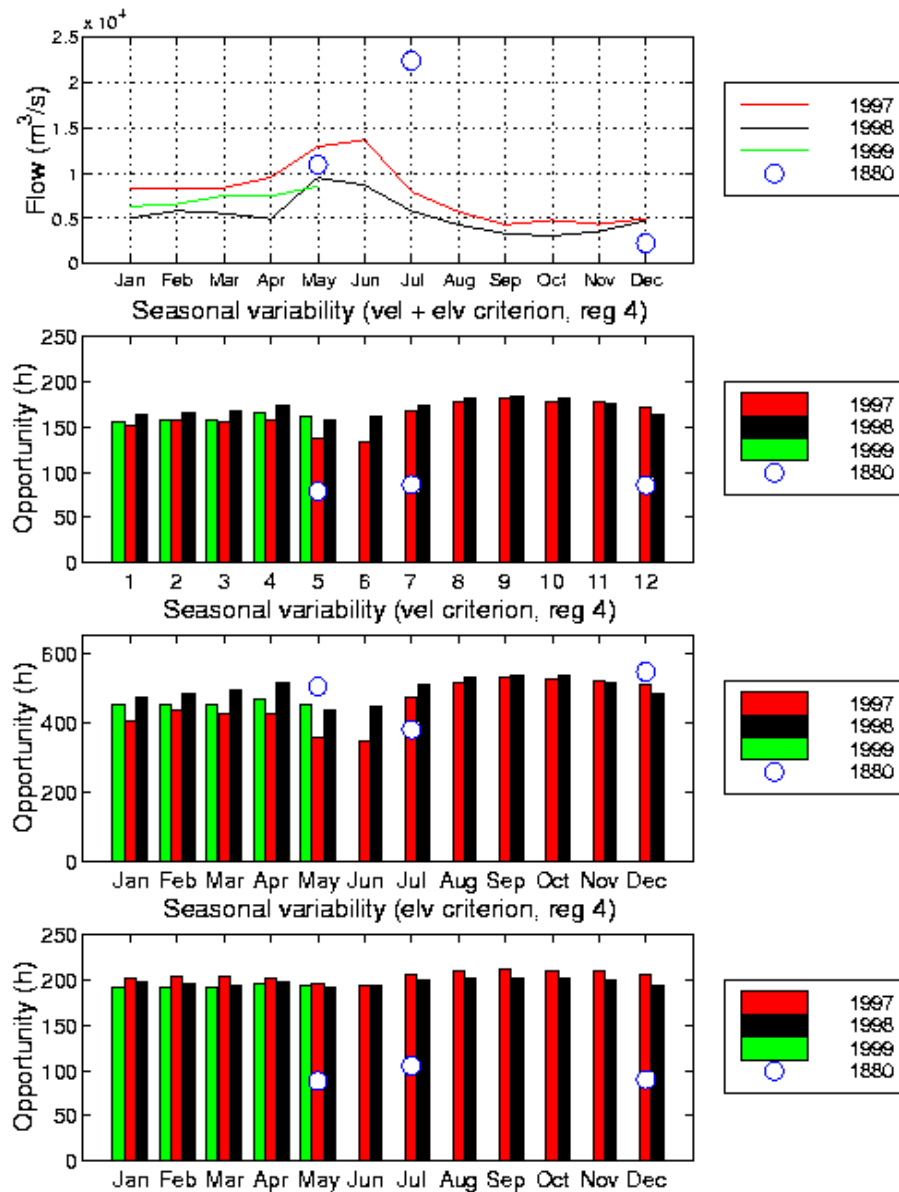
Figure 4.10. River discharge and seasonal variation of estuarine habitat opportunity in Cathlamet Bay (combined, depth, and velocity criteria) for modern vs. pre-development systems. Habitat opportunity is shown in hours normalized to a 30-day month. Habitat opportunity based on the velocity criterion (but not on the depth criterion) shows marked minima during freshet season.

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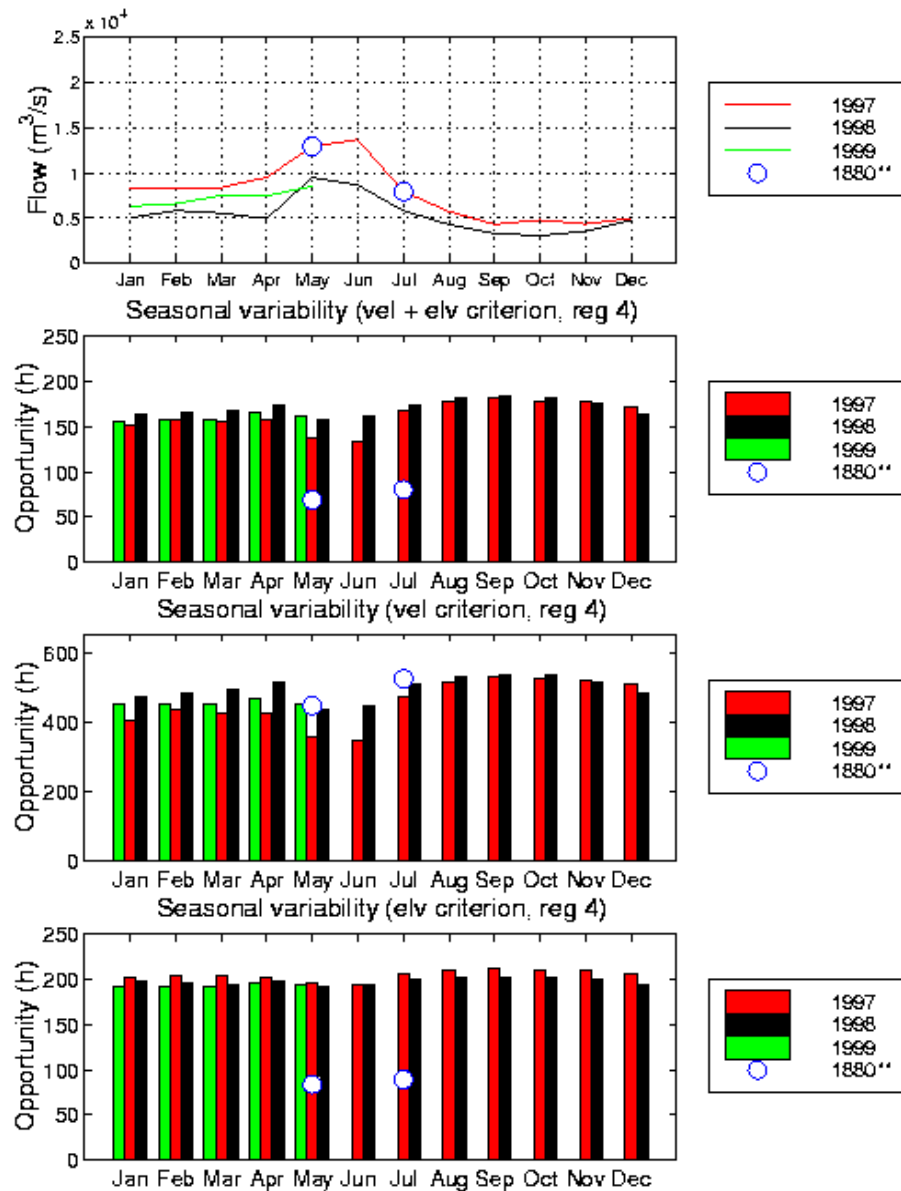
Figure 4.11. River discharge and seasonal variation of estuarine habitat opportunity in Cathlamet Bay (combined, depth, and velocity criteria) for modern bathymetry and flows (1997-1999) and pre-development bathymetry with 1997 flows (1880**; see Table 4.1).
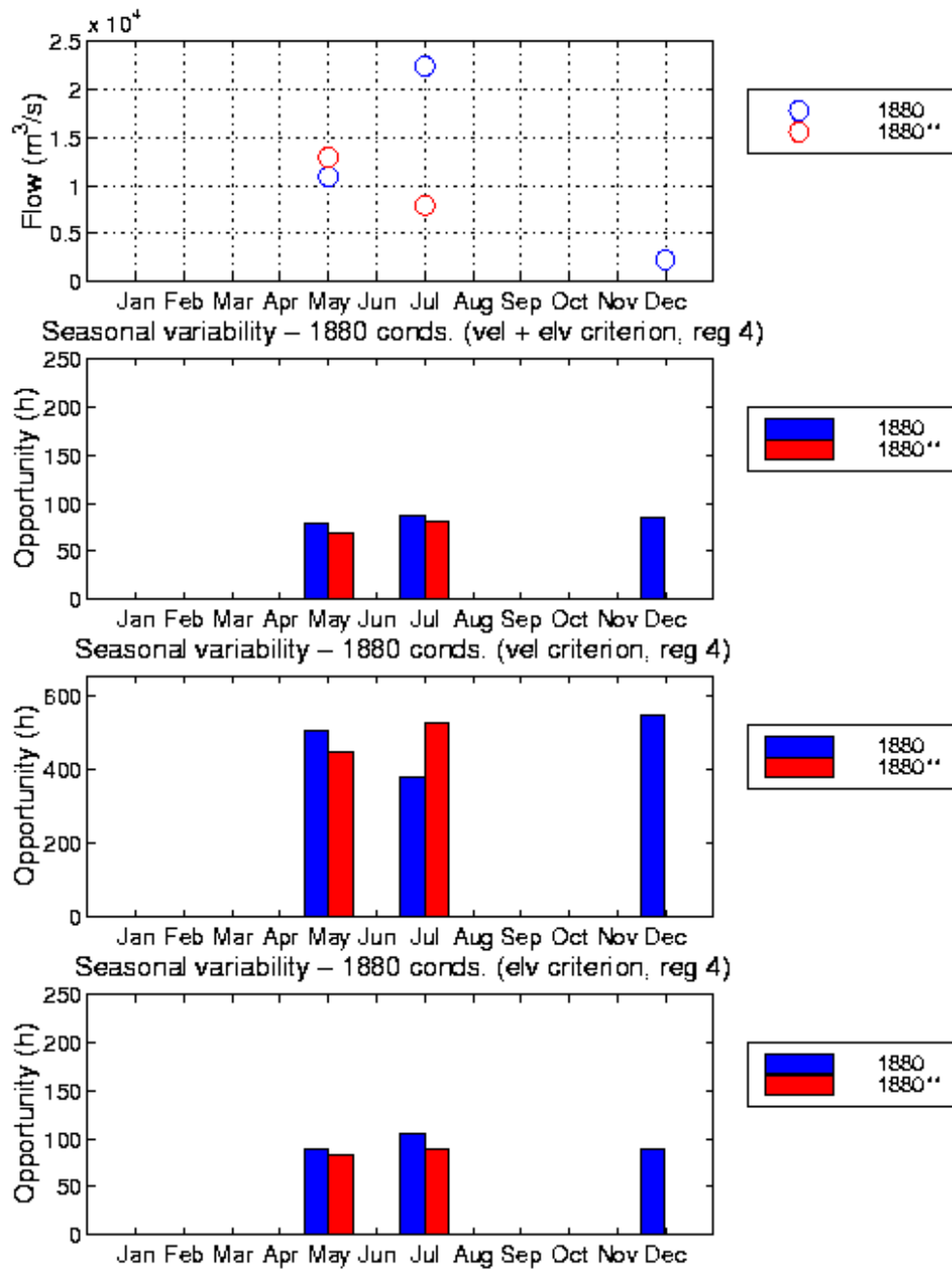
Figure 4.12. River discharge and seasonal variation of estuarine habitat opportunity in Cathlamet Bay (combined, depth, and velocity criteria) for pre-development bathymetry, with pre-development (1880) vs. 1997 river discharges (1880**; see Table 4.1).
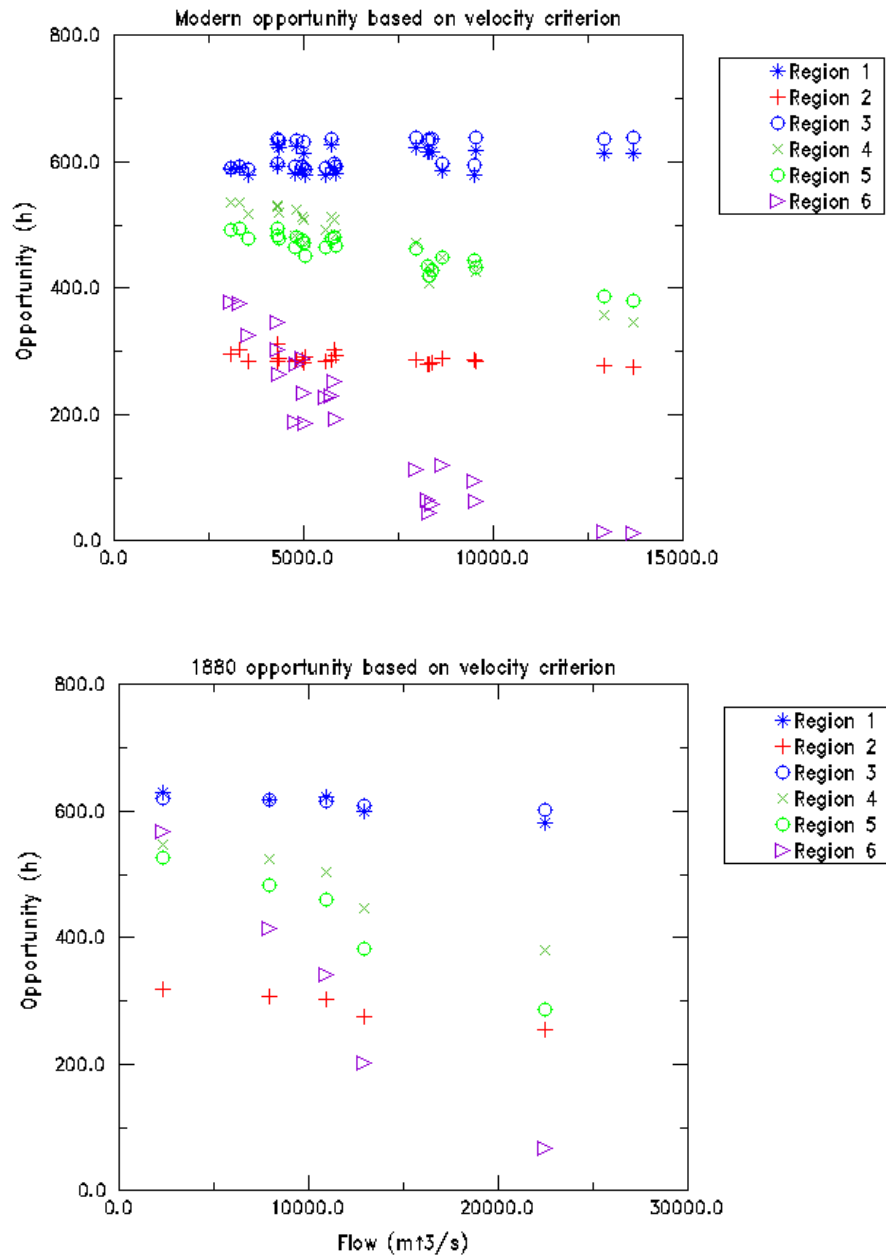
Figure 4.13. Estuarine habitat opportunity as a function of river discharge, for the (a) modern and (b) pre-development systems. Habitat opportunity shown in hours normalized to a 30-day month is based on the velocity criterion. Different sub-regions provide distinct habitat opportunity and have distinctive correlations with river discharge. Similar plots for the depth and combined criteria can be found on the internet (OGI 1999).

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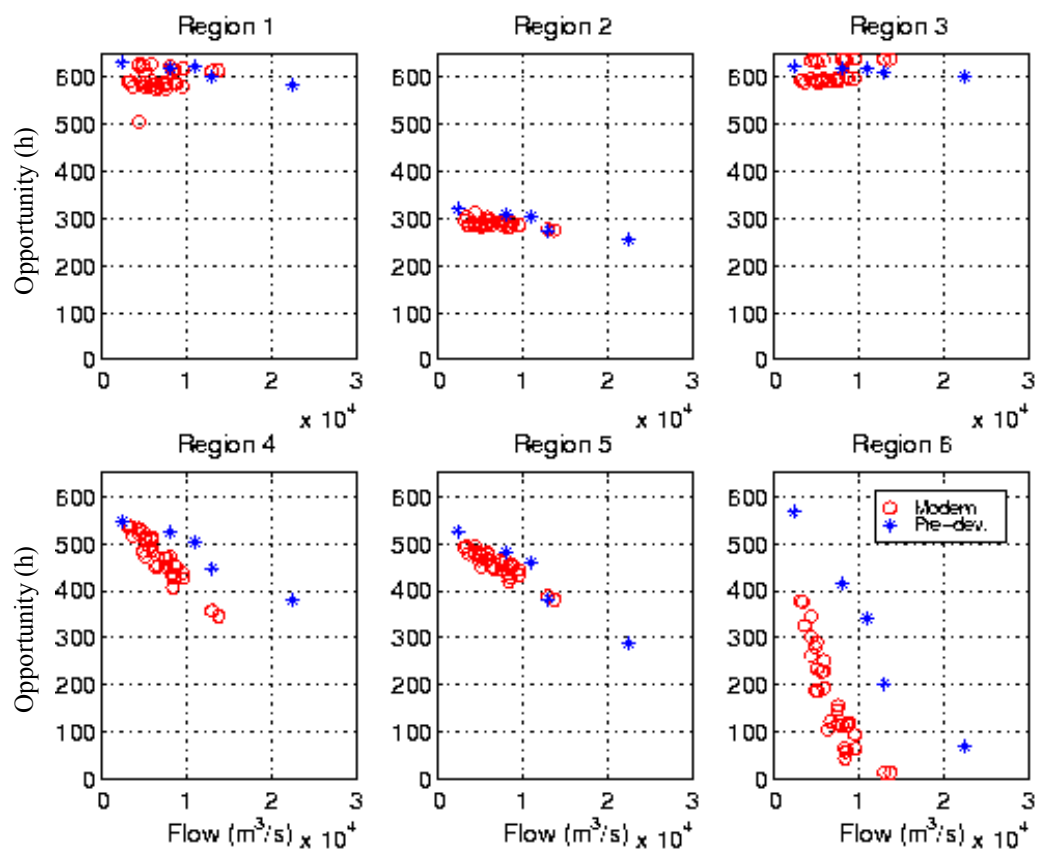
Figure 4.14 Region-by-region comparison of pre-development and modern estuarine
    habitat opportunity as a function of river discharge, for the velocity criterion.
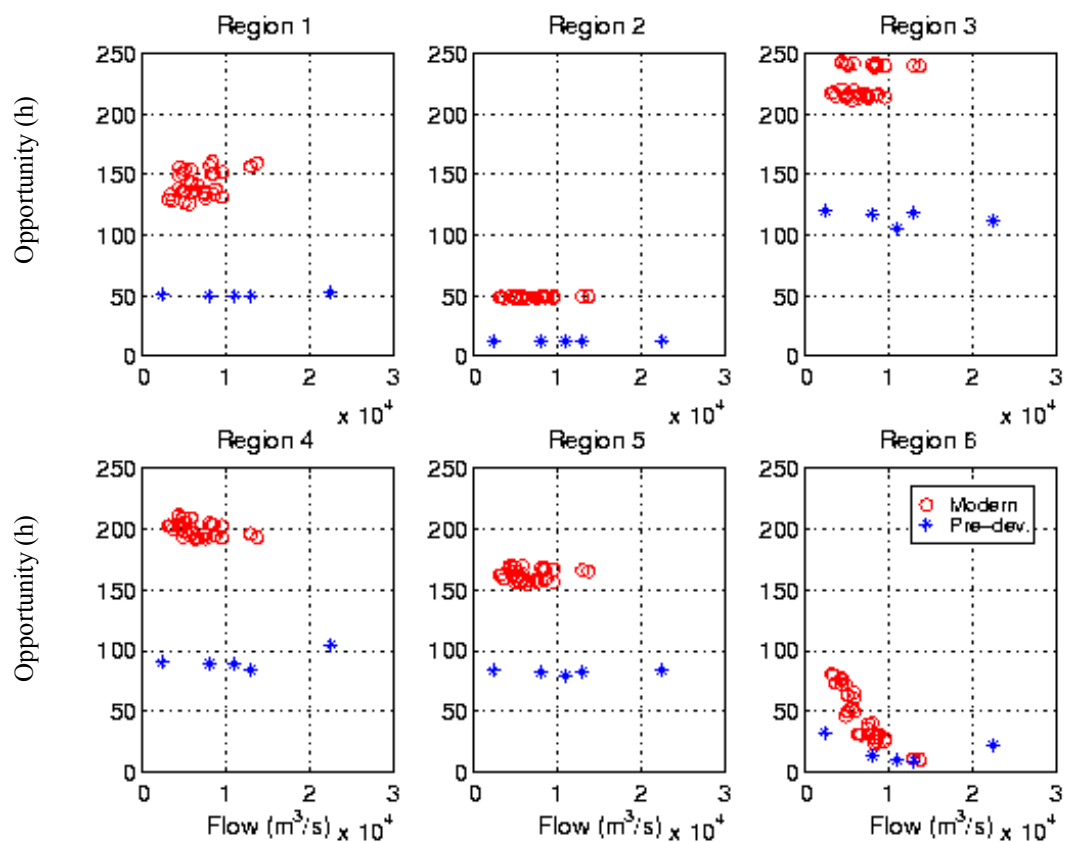
Figure 4.15. Region-by-region comparison of pre-development and modern estuarine habitat opportunity as a function of river discharge, for the depth criterion. Limitations in the representation of modern bathymetry may artificially limit opportunity in the modern system.

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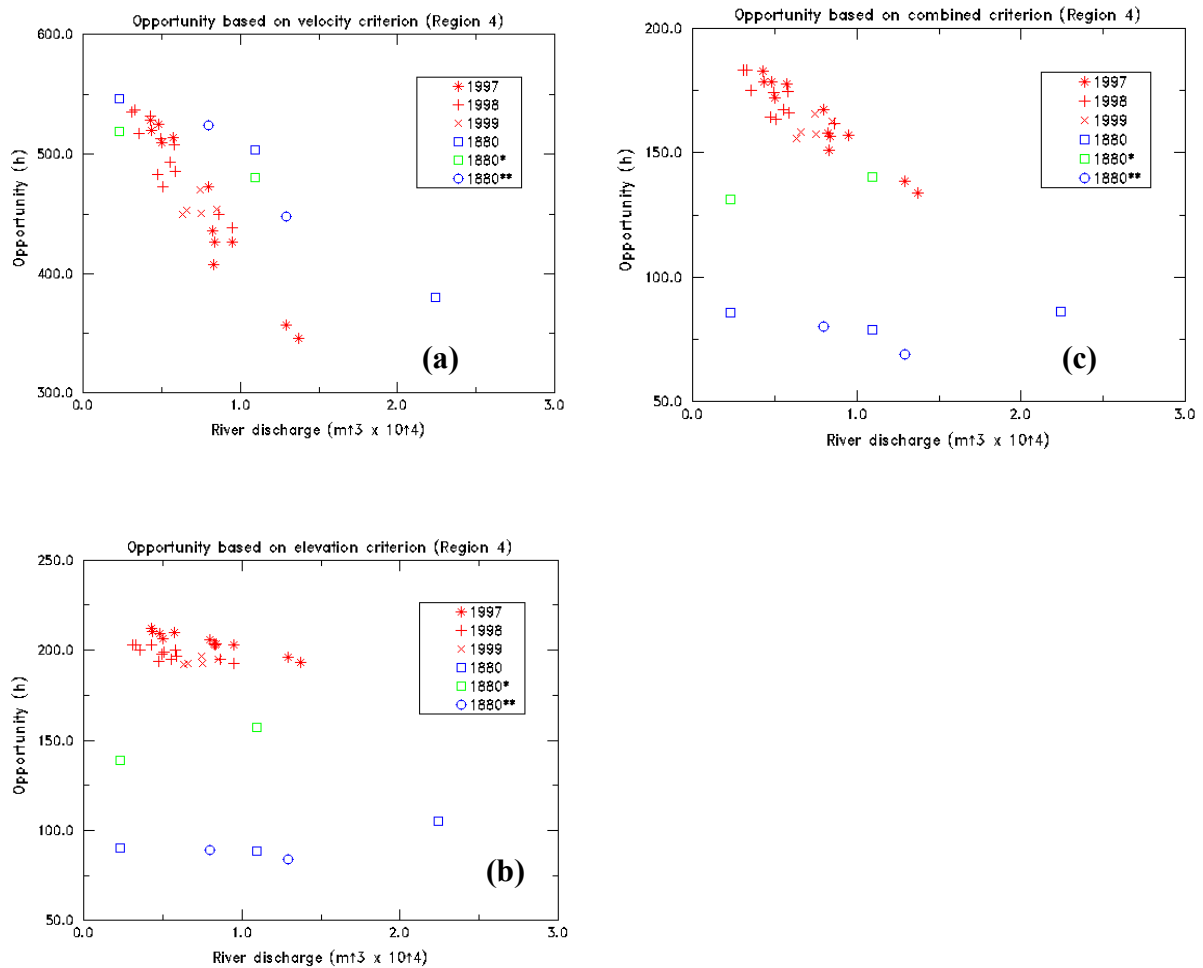
Figure 4.16. Habitat opportunity in Cathlamet Bay as a function of river discharge, for the (a) velocity, (b) depth, and (c) combined criteria. Habitat opportunity shown in hours normalized to a 30-day month is based on the velocity criterion. There are marked differences between habitat opportunity in the modern and pre-development systems.   Sensitivity to controlled changes in bathymetry is much larger for the depth criterion than for the velocity criterion. As discussed in the text, habitat opportunity in the modern system is, for the depth criterion, over-estimated by weaknesses in the model bathymetry. Equivalent plots for other sub-regions can be found on the internet (OGI 1999).

Habitat opportunity in the modern and predevelopment estuaries is not fundamentally different in Regions 1-3 (Fig. 4.14). However, in both Cathlamet Bay (Region 4) and upper estuary (Region 6), the predevelopment opportunity is significantly higher and much more resilient to increases in river discharge. Grays Bay shows insipient, ambiguous signs of the same behavior. The change in Cathlamet Bay is particularly noteworthy, given the apparent importance of that region for subyearling chinook salmon. We would expect closer similarities between Grays Bay (Region 5) and Cathlamet Bay. This lack of similarity is worth further investigation, and may be related to a disproportionate effect of the channel contained in Region 5.

Seasonal variability of habitat opportunity is also distinct from region to region. In Cathlamet Bay, Grays Bay, and the upper estuary, where opportunity decreases with river discharge in both the predevelopment and modern systems, freshet periods consistently provide the lowest habitat opportunity (as shown for Cathlamet Bay in Fig. 4.9). In Youngs Bay, Baker Bay and the lower estuary, freshets also offer minimum opportunity in the predevelopment system, but this is not the case for the modern system, where seasonal patterns are ambiguous.

Interannual variability appears largely associated with and explainable by river-discharge variability, with a notable exception: for Youngs Bay and Baker Bay, habitat opportunity in 1997 is largely uncorrelated with that for 1998 and 1999. For this reason, in Figures 4.13 and 4.14, modern habitat opportunity in Regions 1 and 3 shows anomalous scatter. We find no explanation for this behavior, and recommend that this aspect be further investigated, as it might shed light on the contrast between El Niño (as in 1997) and non-El Niño years. While the possibility that a numerical or processing artifact is biasing the results cannot be excluded, there was no evidence of such an artifact.

Temporal shifts in freshets from June/July in the predevelopment system to May/June in the modern system (Chapter 3) correlate well with shifts in the periods of minimal habitat opportunity in the middle and upper estuary, that is, in the subregions where the correlation of opportunity with river discharge is strongest (Fig. 4.9).

Habitat opportunity is sensitive to the value chosen for the velocity criterion (Fig. 4.17). The 30- and 50-cm s^{-1} criteria applied were within the range of literature values that Beamish (1978) reported for sustained swimming speeds of subyearling chinook salmon. A limited analysis suggests that the alternative threshold velocities yield different absolute estimates of habitat opportunity under varying flow conditions. Yet the general decreasing trend in habitat opportunity with increasing river flows did not change with threshold velocity (Fig. 4.17).

Excluding local detail, habitat opportunity based on the velocity criterion appears only modestly sensitive to the controlled modification of bathymetry introduced in Cathlamat Bay (Fig. 4.15a). Although only indirectly, this suggests that the criterion is robust regarding one of the known weaknesses of the circulation model representation of modern bathymetry in very shallow areas.
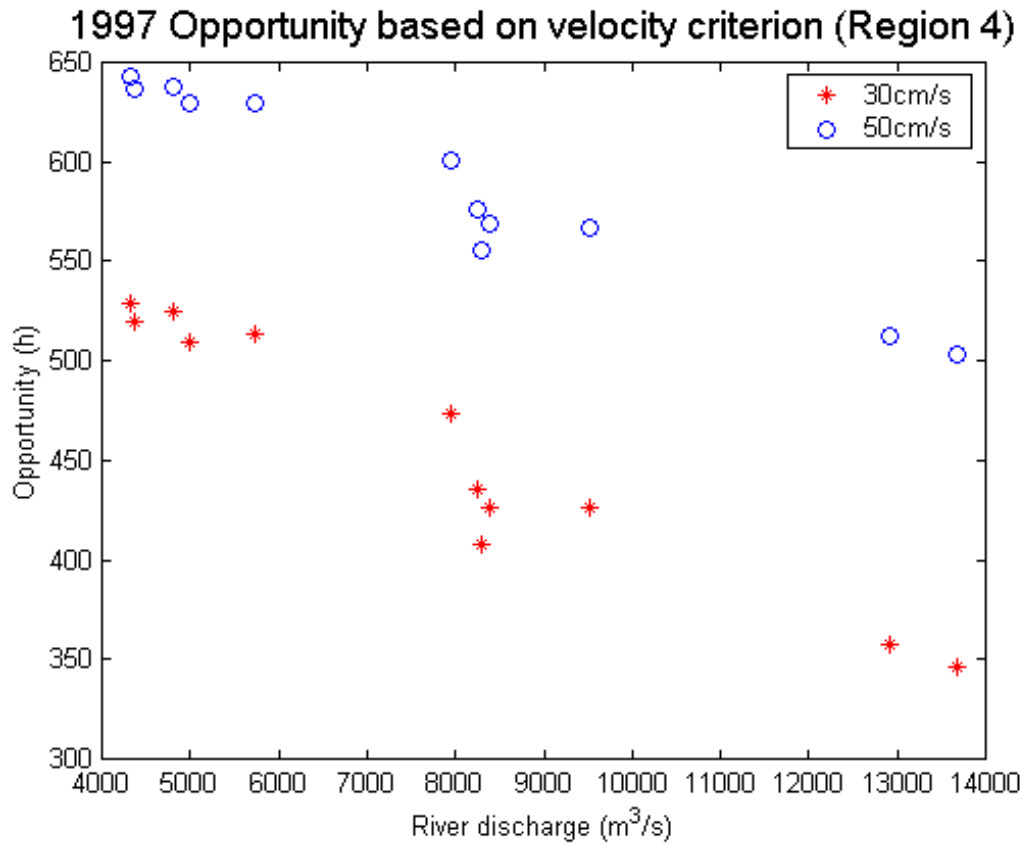
Figure 4.17. Sensitivity of habitat opportunity in modern Cathlamet Bay to the cut-off value of the velocity criterion (50 cm s^{-1} vs. the 30 cm s^{-1} used elsewhere in this work). Differences are very significant, clearly illustrating the need for integration of physical-based criteria with biological data.

Depth Criterion--Distinct patterns and trends also emerge in the characterization of habitat opportunity based on the depth criterion. These patterns and trends were explored in less detail than was shown for the velocity criterion, because the weak representation of shallow-water bathymetry in the modern estuary may have limited the robustness of this criterion.

Results clearly indicate a high degree of sensitivity of habitat opportunity to the controlled modification of predevelopment bathymetry in the shallowest areas of Cathlamat Bay. Artificially deepening that bathymetry greatly increases habitat opportunity (Fig. 4.16b). The important, albeit indirect, implication is that modern habitat opportunity based on the depth criterion is substantially overestimated by our results: indeed, the model's modern bathymetry is least accurate (and artificially too deep) in the shallowest areas of the estuary. While Figure 4.15 shows the comparison between habitat opportunity in the modern and predevelopment systems based on this criterion, overestimation of modern opportunity strongly reduces the meaning of this comparison. The problem is solvable by correcting the modern bathymetry and re-developing the simulation database, but that is not within the scope of this study.

Habitat opportunity is generally much smaller when based on the depth criterion than on the velocity criterion. While the magnitude will vary, the sign of this difference appears unlikely to change when the modern bathymetry is corrected.

Plots of habitat opportunity vs. river discharge still enable separation of the different regions in which the estuary was divided in clusters of similar behavior. However, the composition and behavior of each cluster differ from those of the velocity criterion. In particular, all lateral bays show modest sensitivity to river discharge when habitat opportunity is defined by the depth criterion. Within the lateral bays "cluster," habitat opportunity decreases progressively from Youngs Bay to Cathlamet Bay/Grays Bay and to Baker Bay. Hence, proximity to the ocean is not driving the differences in regional habitat opportunity based on the depth criterion.

Combined Criteria--Habitat opportunity based on the simultaneous satisfaction of the velocity and depth criteria is more stringent than the most stringent of the habitat opportunities based on each individual criterion. This is illustrated in Figure 4.16, which contrasts habitat opportunity in Cathlamet Bay for the individual velocity and depth criteria and for the combination of both criteria. Adding more criteria would likely increase this effect.

Meaningful combination of criteria requires that individual error/uncertainty is comparable for all individual criteria. This is clearly not the case in this investigation, where bathymetric error/uncertainty affects the robustness of the results for the depth criterion much more than they do the results for the velocity criterion. Hence, Figure 4.16c is included primarily to illustrate a potential approach for synthesizing information by applying multiple habitat criteria. Use of this figure to contrast modern and predevelopment opportunity is strongly discouraged.

Figure 4.16 suggests the interesting hypothesis that the modern system may offer better habitat opportunity up to some critical discharge range, beyond which the predevelopment system is superior. However, before this hypothesis can be evaluated, a critical understanding of the true bathymetry in the shallow regions around the estuary's islands must be undertaken. This is not within the scope of the present exercise and represents a limitation of the findings and a gap in the information that should be filled.

Residence Times

Residence times are important descriptors of estuarine behavior (e.g., Pilson 1985, Zimmerman 1988). However, no real consensus exists on the definition of "residence time," mostly because the definitions are "operational." The operational definition of residence times for this study is purely hydraulic, excluding consideration of settling/erosion or self-motion of the particles.

Sommerfield (1999) used the method proposed by Oliveira and Baptista (1997) to investigate residence times in the Columbia River. This method is based on time-consuming numerical simulations. Using pre-existing numerical simulations of circulation, a large number of virtual particles are released inside the estuary and followed to determine the time that they take to leave the estuary. Information from individual particles, mapped at their starting locations, is then aggregated into estuary-wide isolines of residence times.

Because of the previous work of Sommerfield (1999), and of the computational expense involved in the method, limited simulations of residence times were conducted (OGI 1999) for the modern estuarine bathymetry only.

The results supported Sommerfield's (1999) analysis and findings. Residence times in the estuary typically were short, often in the range of one to a few tidal cycles (Figs. 4.18-4.20). Even short residence times varied significantly in space, with the longest retention times for particles in shallow, constrained environments. Lateral bays are a prime example of a constrained environment in an estuary (Fig. 4.18). Local freshwater inputs, which can significantly affect residence times in such constrained environments, are unfortunately difficult to quantify and were not included in the simulations.

Residence times decreased with increasing river discharge, but time of release and tidal coefficients introduced significant variation around this trend (Fig. 4.19). Residence times were dependent on the time of release of the particles within a tidal cycle. This dependency is complex, and the simplistic notion that "residence times are smallest for particle releases during ebb" can be misleading depending on the location in the estuary (Fig. 4.20). Aside from lateral bays, residence times tended to increase with distance from the mouth of the estuary (Figs. 4.18 and 4.21). Also, a time series of residence times in the upper estuary, particularly upstream from Tongue Point, exhibits much stronger evidence of "tidal stirring" and thus less organized flushing patterns (Fig. 4.21).

Results presented above and in Sommerfield (1999) provide insights into patterns of variability of residence times in space and time (below) that are important complements to our understanding of the net hydraulic transport in the Columbia River estuary. However, an indicator that is simpler to calculate was chosen to investigate net hydraulic transport (see residual velocities below) because it facilitated portrayal of the dependencies of natural system variability on postdevelopment changes.

Residual Velocities

Residual velocities (defined as the net velocity at a fixed point, over a predefined time period that is typically a multiple of the tidal cycle) are an Eulerian complement and counterpart to residence times, which are inherently Lagrangian. Residual velocities are much faster to compute given a pre-existing simulation of the flow field, and results are easier to synthesize and interpret.

Residual velocities characterize net hydraulic transport from the perspective of an observer fixed at a specific location, while residence times provide the perspective of an observer being passively transported by the water. Residual velocities are much faster to compute given a pre-existing simulation of the flow field, and results are easier to synthesize and interpret.

Residual velocities were computed as monthly averages for both modern and predevelopment conditions across the entire simulation database. Within each month, residual velocities were also computed as daily averages, and daily values were used to estimate standard deviations over the month. Isolines of monthly residual velocities and standard deviations are available on-line, as are plots that depict variations in residence times (integrated over the entire estuary) with season and river discharge (OGI 1999)

Using estuary-wide integrated values, it becomes clear that residual velocities have significant seasonality, reflecting the seasonality of river discharge (Fig. 4.23). Freshets occurred later in the predevelopment Columbia River estuary compared to the modern system. This outcome is reflected in residual velocities and confirms the findings in Chapter 3.

Seasonal trends were consistent with the fact that residual velocities tend to increase with increasing river discharge in an approximately linear manner (Fig. 4.24). Modern and predevelopment systems showed distinct correlation. For the same river discharge, the modern system exhibited higher residual velocities than the predevelopment system, likely reflecting a higher degree of canalization (hence, less buffer regions) in the modern system. This suggests that net hydraulic transport is less sensitive to flow changes in the predevelopment estuary than it is in the modern estuary. However, the highest residual velocities corresponded to July 1880, the highest-discharge month on the simulation database. Predevelopment freshets were therefore more effective flushing events than modern freshets, even if the modern system is more canalized and more responsive to increases in river discharge.

Estuary-wide residual velocities show little sensitivity to the controlled bathymetric changes introduced in Cathlamet Bay (Fig. 4.25). Local effects in the areas of bathymetric change are, naturally, more significant, but uncertainties derived from not knowing the exact bathymetric configuration of the estuary in the predevelopment period appear to be a relatively minor concern. This finding is consistent with simulations of habitat opportunity based on the velocity criterion, which were similarly insensitive to bathymetric uncertainty.

Daily variations of residual velocities (as measured by standard deviations) are significant: for instance, local maxima of the standard deviation of the daily residual velocities exceed 15 cm s^{-1} in May 1880 (Fig. 4.26, top). These daily variations follow correlations with river discharge (Fig. 4.26, bottom) that are similar to those described for the monthly averages.
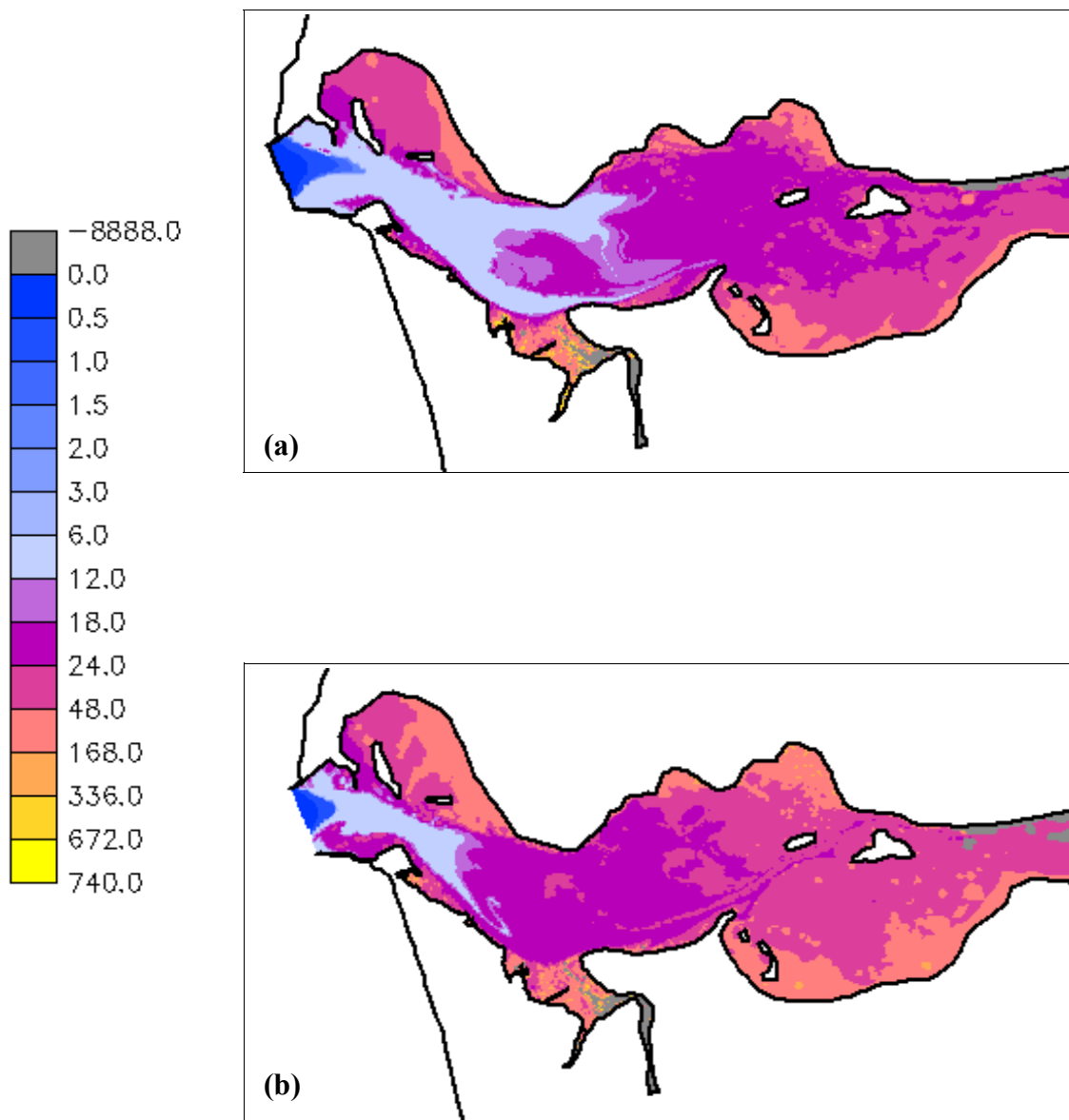
Figure 4.18. Residence times for (a) high discharge conditions in June 1997 and for (b) low discharge conditions in July 1997. Large percentages of the estuary have residence times of the order of one or a few tidal cycles. Lateral bays have substantially higher residence times than the main stem. Residence times are noticeably smaller for high discharges (adapted from Sommerfield 1999).
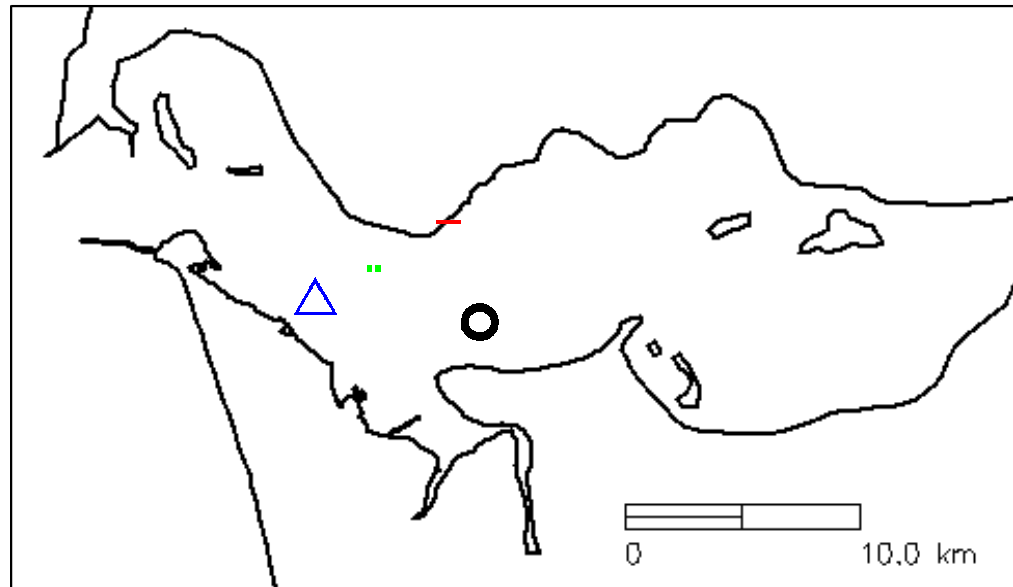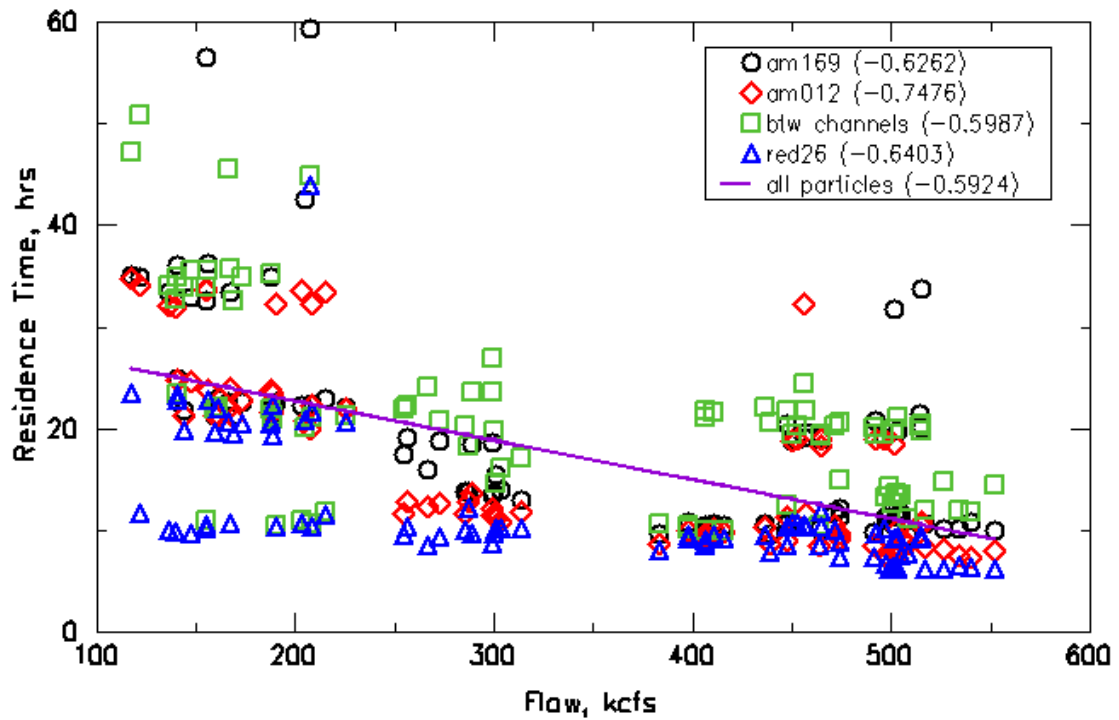
Figure 4.19. Influence of river discharge on residence times, at four fixed locations in the estuary. The stations marked with a triangle and circle were in the navigation channel (near CORIE stations red 26 and am169, respectively), the station marked with a diamond was in the north channel (near CORIE station am 012), and the station marked by a square was in the shallow divide between channels.   Results show that although residence times tend to decrease with increasing river discharge, the correlation is complex, possibly because of tides and their non-linear interactions with local topography and river discharge (adapted from Sommerfield 1999).
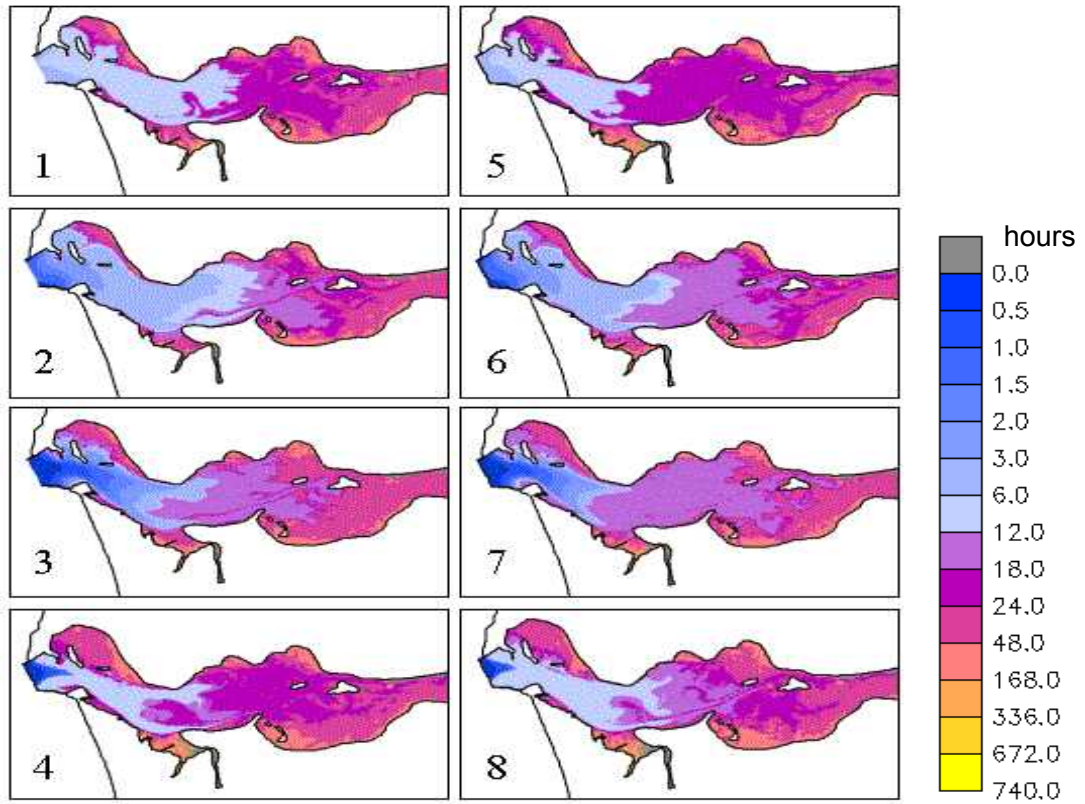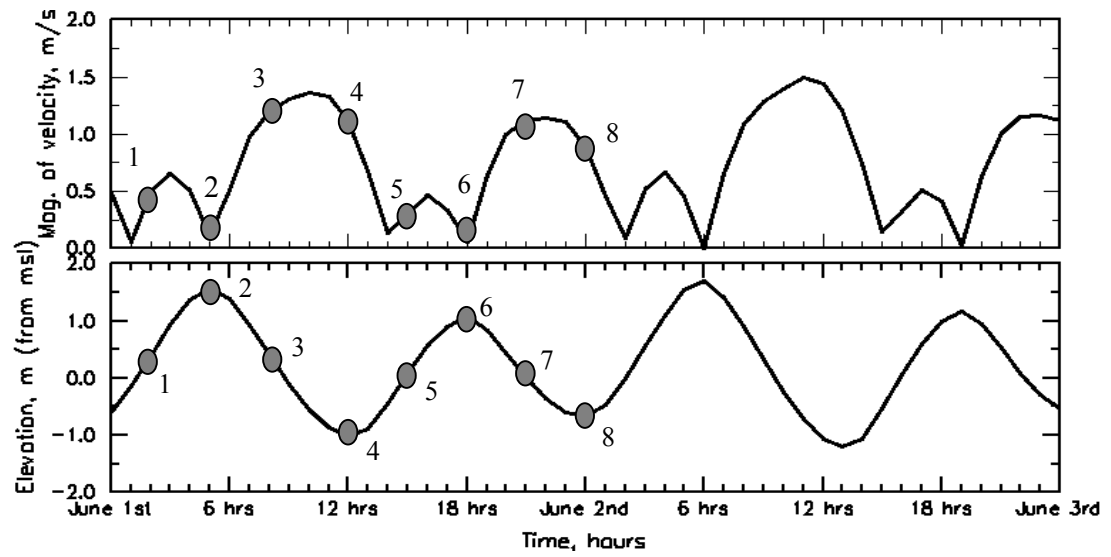
Figure 4.20. Residence times for June 1997 at eight release times over the tidal cycle (adapted from Sommerfield 1999).

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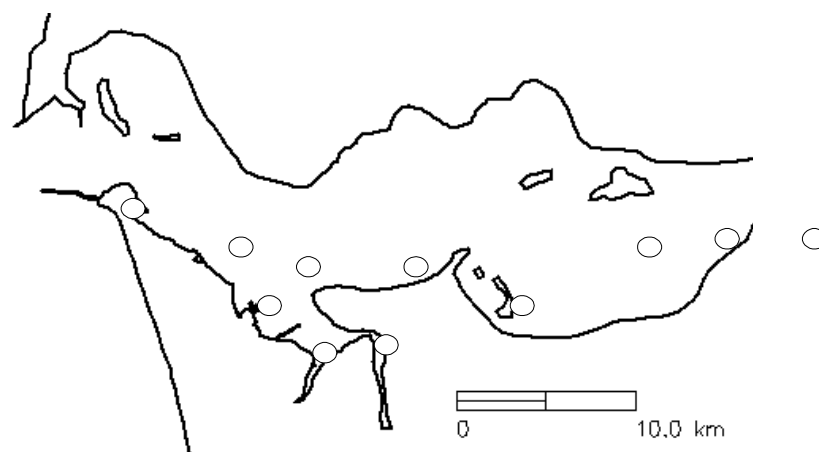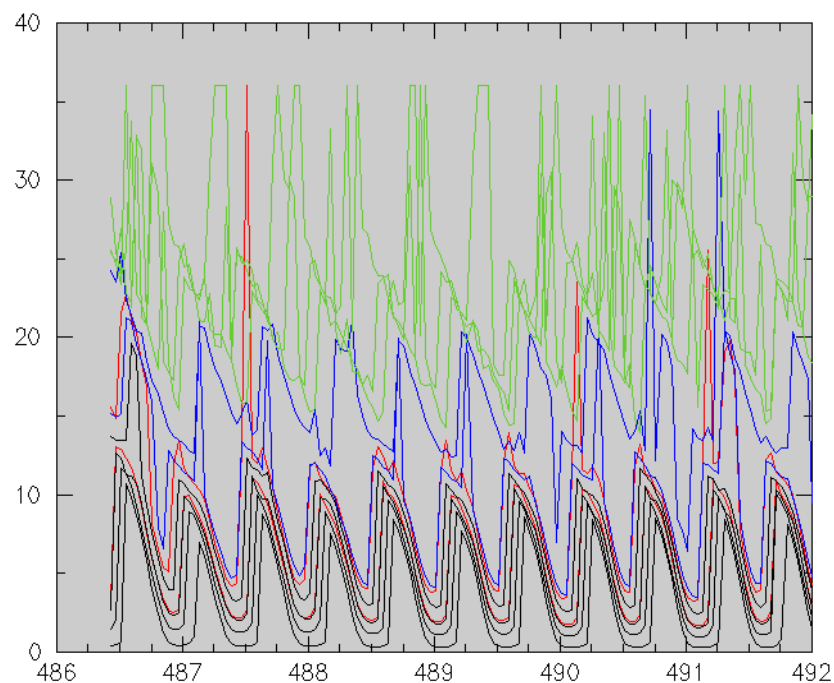
Figure 4.21. Time-series of residence times (in hours) for a 5[+]-day period in June 1997 at selected locations in the estuary. All locations are either in the navigation or the north channel. With increasing distance from the mouth, there is a progressive evolution from a tidal-controlled, quasi-periodic pattern of short (<12.4 hour) residence times to a more irregular pattern of residence times of the order of multi-tidal cycles (graph is cropped at 37.2 hours). This pattern of increasing disorganization toward the upper estuary reflects a higher opportunity of upper-estuary, longer-residence-time particles to steer away from the main channels, in particular during tidal reversals.
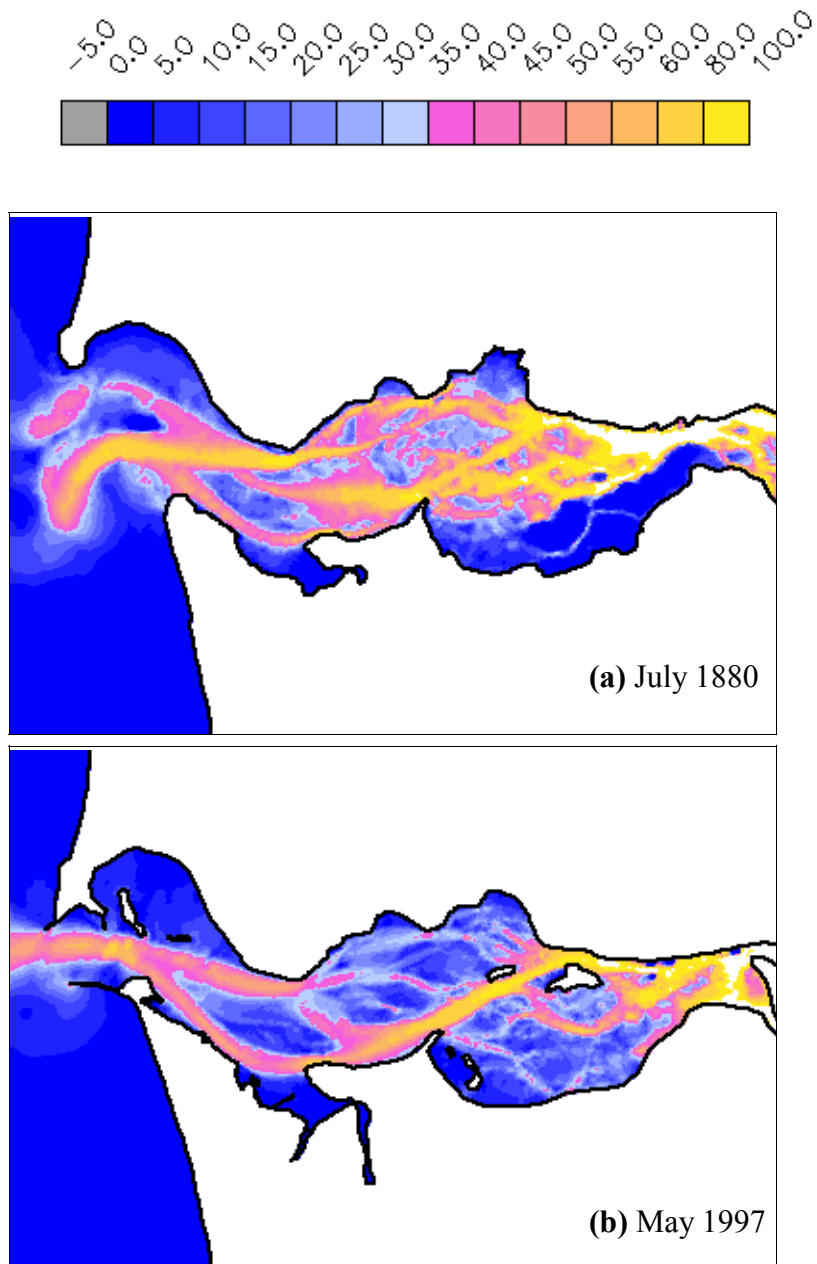
Figure 4.22. Residual velocities for high discharge months in the (a) pre-development and (b) modern systems. Differences follow closely the modifications in topology of the two systems, and in particular in the channel layout.
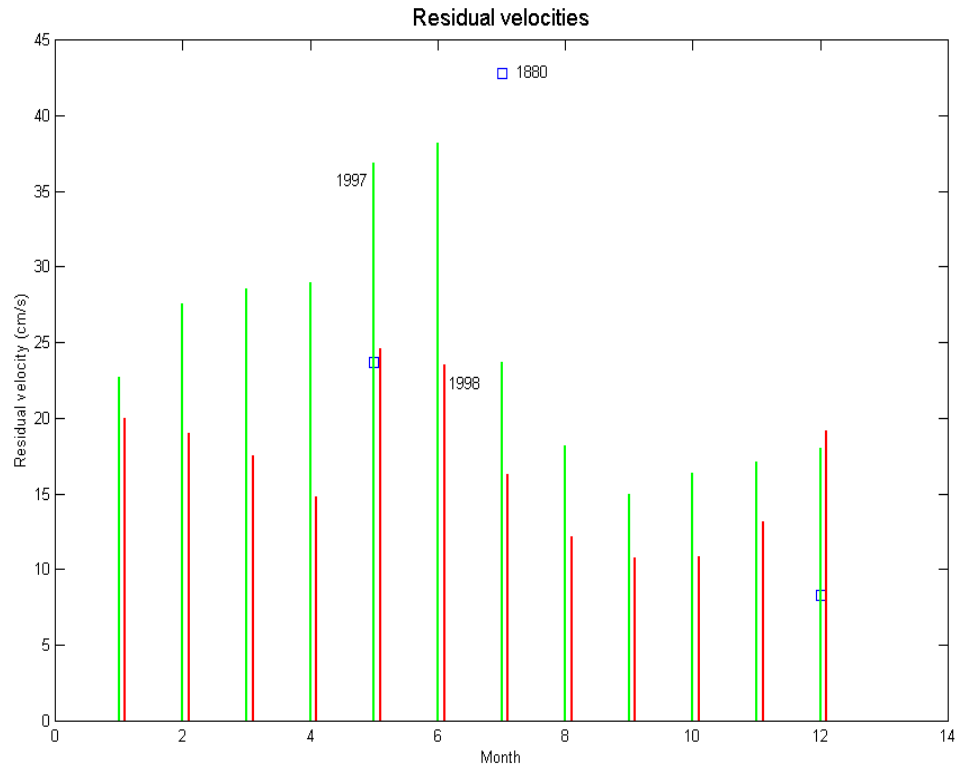
Figure 4.23. Residual velocities show marked seasonality, with highest values corresponding to freshet months. Freshets occurred later in the pre-development system, a shift that is reflected in the residual velocities. There is a significant inter-annual variability (e.g., 1997 vs. 1998), with high discharge years having larger residual velocities. All values of residual velocity shown in this figure are estuary-wide, having been obtained by spatial integration of local values.
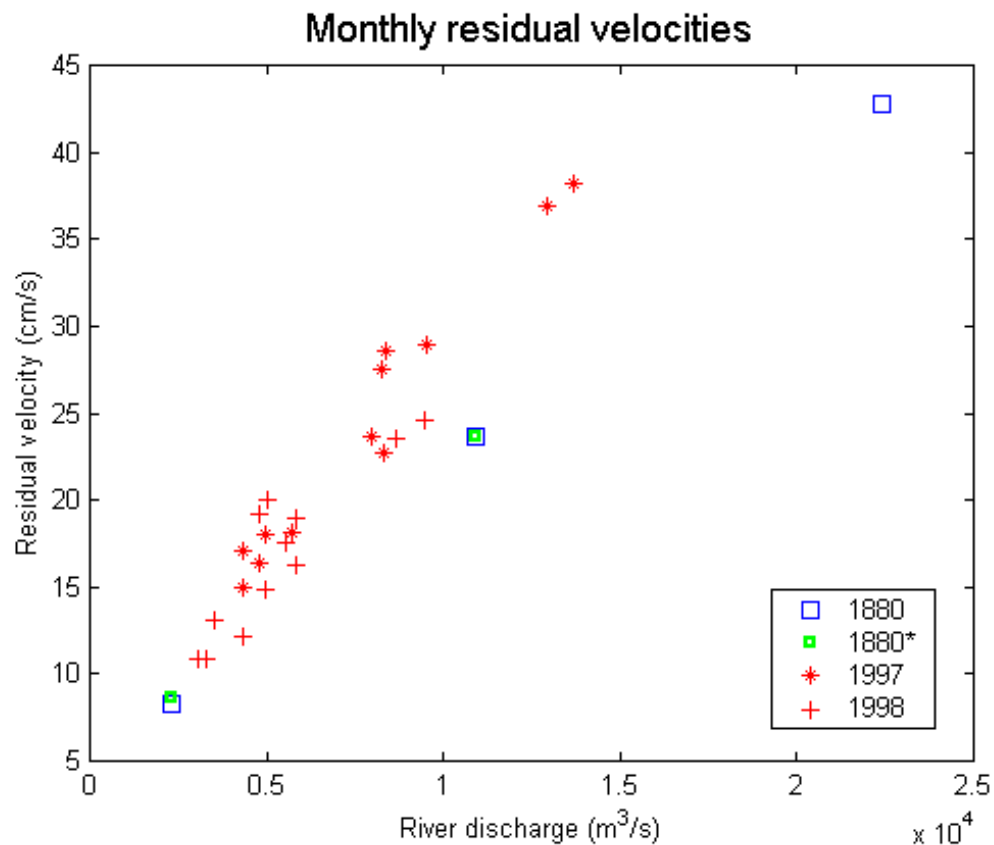
Figure 4.24. Residual velocities increase sharply with increasing river discharge, with what appears to be a quasi-linear correlation. Pre-development and modern systems have distinguishable correlation fingerprints. For an equal river discharge, the modern system has higher residual velocities than the pre-development system, possibly because of a higher degree of canalization. Values of residual velocity shown in this figure are estuary-wide, having been obtained by spatial integration of local values. Estuary-wide residual velocities show little sensitivity to controlled changes in Cathlamet Bay bathymetry (1880 vs. 1880*; see Table 4.1).

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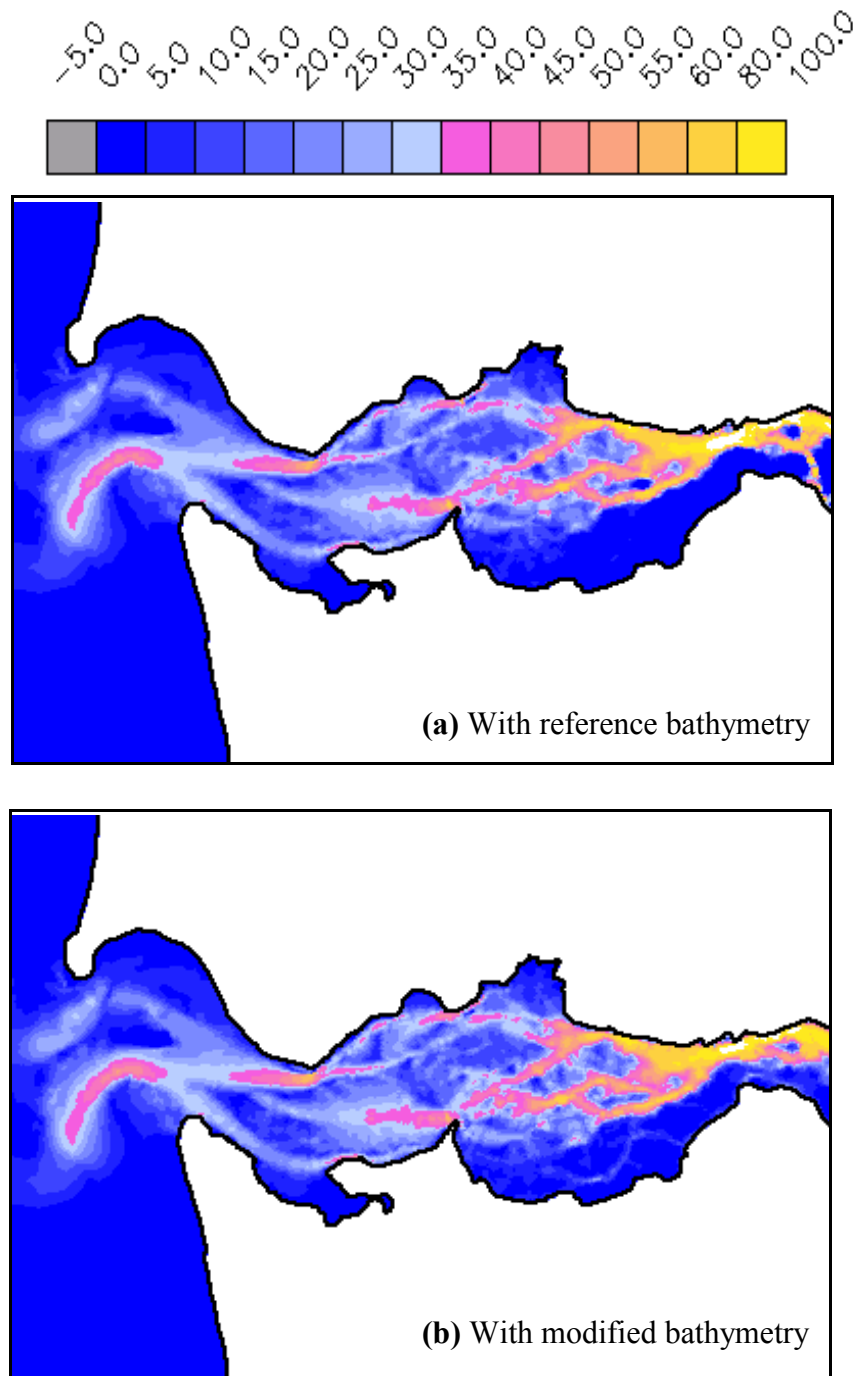
Figure 4.25. Outside the area directly affected, residual velocities show very little sensitivity to controlled changes in the pre-development Cathlamet Bay bathymetry. Results shown are for May 1880.
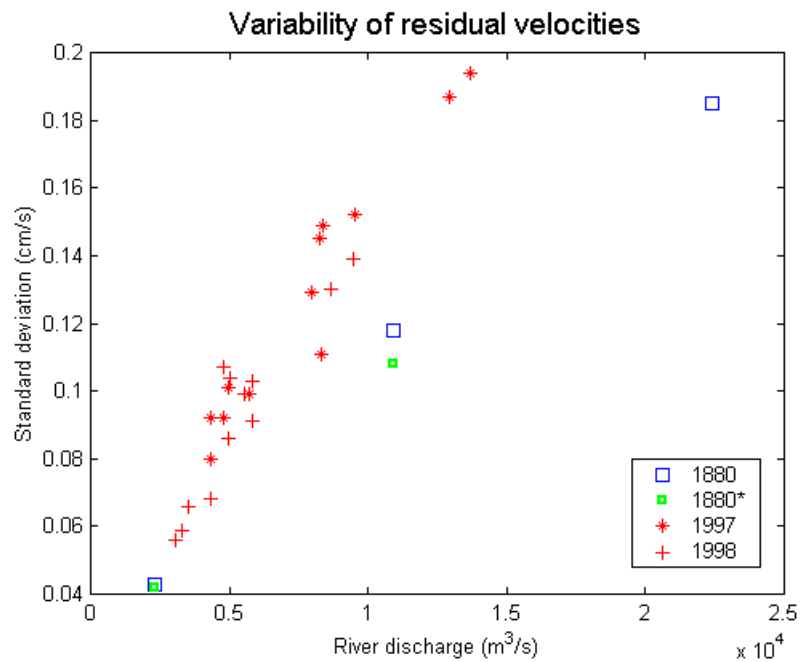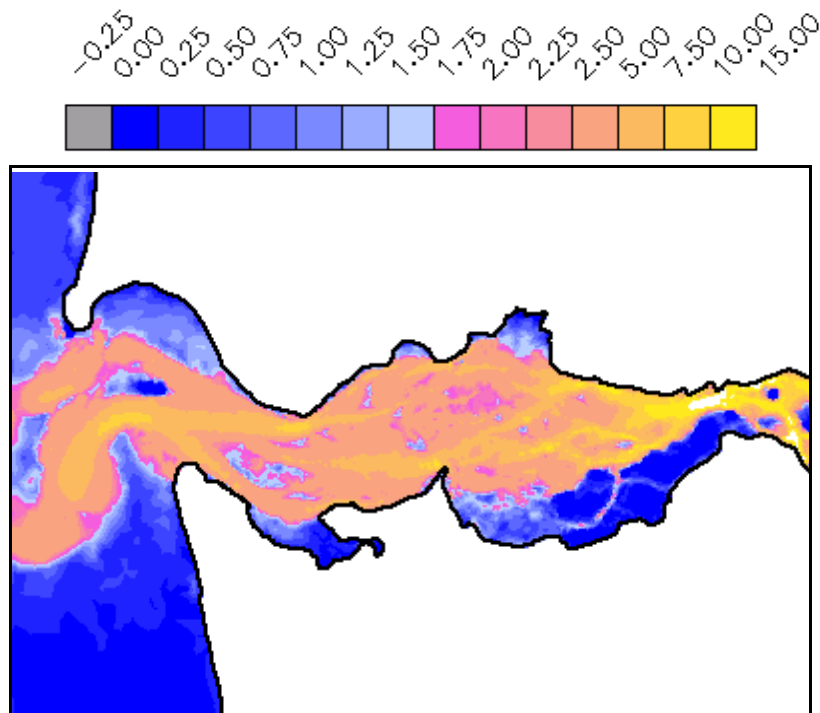
Figure 4.26. Variations of daily averaged residual velocities over the month are shown in isoline form for May 1880, and in form of estuary-wide correlation of "standard deviations" with discharge for selected modern and pre-development years. Patterns and trends are very similar, scale aside, to those of monthly-averaged residual velocities.

Conclusions

Methodology

Numerical circulation models appear to be effective tools for identification and characterization of physical patterns and trends in the Columbia River, and their response to external change, such as river flow. Results presented in this review are based on a circulation model that should still be improved upon. Areas improvements are most needed are described below.

Representation of Modern Bathymetry, Particularly in the Shallowest Areas

Motivation--This improvement is essential to establish confidence in the model results for shallow areas. In particular, it is expected that revised modern bathymetry will lead to a significant decrease in the physical habitat opportunity predicted on the basis of the depth and combined criteria in the present estuarine system.

Comments--Meaningful progress can be made by a thorough revision of the bathymetry of the model, using existing survey data and aerial photography. However, new bank-to-bank surveys are recommended, because important shallow areas of the estuary have not been surveyed since the late 1950s.

Inclusion of Salinity and Temperature Propagation

Motivation--Salinity and temperature are key physical indicators, without which the characterization of habitat opportunity for juvenile salmon is incomplete. Also, inclusion of vertical structure and density effects will improve the model's representation of velocities and transport processes.

Comments--A recently developed three-dimensional baroclinic circulation model for the Columbia River (Myers and Baptista 2000) is a major step toward addressing this need. The new model is not only more complete in its representation of physics, but is also significantly faster. The new model still requires a systematic validation.

Criteria for physical habitat opportunity have a biological rationale but remain untested. The chosen threshold values for each criterion (velocity and depth) affect the absolute values for habitat opportunity more than their trends under varying flow conditions.

Implications for Salmonid Rearing Habitat

The characterization of habitat opportunity needs to be further enhanced by refining the circulation model and broadening the suite of habitat indicators before we can confidently quantify changes in physical habitat opportunity between the predevelopment and modern systems.

The results enable, however, novel and powerful ways to conceptualize habitat opportunity in the estuary, and its response to physical change. In particular, there is good supporting evidence for the following interpretations:

- Habitat opportunity is strongly controlled by bathymetry and, at least for the upper estuary, river discharge (Fig. 4.13, Regions 4-6). Tidal effects were not systematically analyzed, but tides are likely another important factor controlling habitat opportunity.

- Physical relationships to habitat opportunity are distinct in different regions of the estuary. Differences appear strongly correlated with proximity to the ocean and with environment type (e.g., Figure 4.13). The estuarine subregions used in this study were chosen to coincide roughly with those used in the CREDDP surveys (Simenstad et al. 1990). However, it is possible, and perhaps advisable, to use a finer or different definition of sub-regions (e.g., Figure 4.5b).

- Habitat opportunity varies seasonally, and is often smallest during freshets. The timing of minimum habitat opportunity often reflects known shifts in the timing of freshets from predevelopment to modern times.

- The modern and predevelopment systems are distinctive in terms of their morphology, residual circulation, and habitat opportunity.

- Trends and patterns of habitat opportunity depend on the criteria chosen to depict the physical requirements and thresholds of juvenile salmon.

- While it may be useful to combine two criteria, or more generally, multiple habitat opportunity criteria, meaningful interpretation of the combined results requires a firm handle on relative errors and uncertainty. This is beyond the scope of this work but is arguably within reach of available technology.

- The velocity criterion is much less sensitive than the depth criterion to known weaknesses of the model in representing modern bathymetry (Fig. 4.16). The difference in error/uncertainty for the two criteria prevents their meaningful combination.

- Both the depth and velocity criteria have uncertainties related to the threshold values (Fig. 4.17), which cannot be robustly addressed without a more tightly-coupled physical/biological analysis. Such an interdisciplinary approach should be specifically emphasized in future studies of estuarine habitat opportunity.

- The increased canalization of the Columbia River estuary, from predevelopment to modern times, is visible across all indices of net hydrodynamic transport. Particularly revealing are maps of spatial distribution of residual velocities (Fig. 4.22). Moreover, these effects may be significantly underestimated in this analysis because historical and present-day floodplain, riparian, and wetland habitats are not fully represented in the bathymetric base maps used for our simulations. Effects of canalization may be greater if we could also account for widespread diking and filling of peripheral shallow-water habitats.

- There is a general level of consistency across observed trends in residual velocities and in habitat opportunity. Exploration of specific correlation between indices of net hydrodynamic transport and indices of physical habitat opportunity were beyond the scope of this investigation but should be pursued in the future.

5. ESTUARINE HABITAT CAPACITY

Introduction

While *opportunity* to access rearing habitats (Chapter 4) is a critical factor affecting estuarine rearing by juvenile salmon, the *capacity* of the accessible habitat to support these fish is equally important. The product of habitat opportunity and capacity, in conjunction with the capability of a salmon population's life-history structure to utilize diverse habitats, is likely the primary determinant of population persistence and resilience (see Chapters 1 and 2; Simenstad and Cordell 2000).

Capacity refers to attributes of estuarine habitats that affect both juvenile salmon feeding and efficient assimilation of their diet to support growth and elude predators. The structural complexity and distribution of estuarine habitats may further determine whether they provide functional refugia from potential predators. Within the range of each attribute that affects capacity, there are optimal conditions that can enhance feeding and growth as well as reduce predation.

Moreover, capacity factors are not always independent and mutually exclusive. For instance, while lower water-turbidity increases the reactive distance for sight-feeding fish like juvenile salmon, and thus enables earlier detection of prey, lower turbidity also increases the visibility of juvenile salmon to aquatic and aerial predators. However, quantifying the impact of changes in the capacity of the estuary to support estuarine-dependent salmonid species and life-history stages is difficult to quantify.

Complex relationships among the many factors affecting salmon, including primary producers in estuarine food chains, prey production and availability, and salmonid vulnerability to predators cannot be simulated in the same straightforward way as modeling water elevations and current velocities. In fact, the intrinsic assumption that food or predation in the estuary may limit juvenile salmon productivity, or that there are carrying capacity limitations for juvenile salmon in the Columbia River estuary, has never been rigorously tested.

Foraging Habitat and Food Web Changes

There is substantial evidence and inference that the potential productive capacity of the estuary has declined over the last century. Together, habitat removal by diking and filling, shifts from a macrodetritus-based to microdetritus-based food web, and introductions of non-native species have likely disrupted food webs and other estuarine functions that historically supported juvenile salmon. However, the only impacts to salmon that have been substantiated involve reductions in marshes and forested wetlands and the simplification of distributary channels.

The importance of estuarine rearing to salmon recruitment has not been fully tested. Reimers (1973) and Levings et al. (1989) have demonstrated that estuarine rearing of juvenile salmon contributes to total survival under some circumstances.

However, the processes critical to improved survival are not well defined. Most studies have inferred that total salmon growth and duration of residency in the estuary are key determinants of survival.

Yet perhaps equally important is the variability in the times and sizes of salmon entry to the North Pacific Ocean, which are influenced by seasonal and climatic changes and the spatial distribution and connectivity of estuarine rearing environments. As demonstrated by Levings et al. (1989) for ocean-type chinook in the Campbell River estuary, British Columbia, estuarine residence does not always result in higher survival. This has prompted us to adopt the concept that the diversity of salmon life history types and a mosaic of alternative habitat types and conditions necessary to support these varied behaviors may be more important indicators of salmonid performance than just residence time and growth in the estuary (Chapter 2).

Throughout the scientific literature, ocean-type chinook and other species and life-history types (e.g., chum salmon) considered most "estuarine dependent" (see Chapters 2 and 6) are documented to rear in estuaries for up to several months and use shallow-water habitat and prey resources through at least the early portions of their residency (see life-history syntheses in Groot and Margolis 1991; see also Levy et al. 1979; Levy and Northcote 1981, 1982; Healey 1982; and Simenstad et al. 1982 for further detail, especially for the Fraser River, which may be the most comparable system to the Columbia River estuary represented in the literature).

Recent and ongoing studies from other estuaries of the region confirms that small, subyearling ocean-type juvenile salmon, typically, and perhaps even preferentially, occupy shallow habitats and particularly emergent marshes and forested wetlands. In freshwater and brackish habitats, juvenile salmon feed extensively on emergent insects (particularly larvae, pupae, emergent chironomid and other dipteran flies, and aphids) and epibenthic crustaceans (e.g., mysids, gammarid amphipods) (e.g., Levy and Northcote 1982, Miller and Simenstad 1997, Simenstad and Cordell 2000) and forage more specifically on epibenthic crustaceans (e.g., gammarid amphipods, harpacticoid copepods) in more saline habitats.

The diet composition and distribution of juvenile salmon far into shallow tidal-channels and sloughs (during high tide) suggest that small fry and fingerlings, such as subyearling chinook, are rearing in direct association with the vegetated edges of estuarine wetlands (Levy and Northcote 1982, Simenstad et al. 2000). During periods of low tide and reduced river flow, these fish must feed in shallow waters at lower tidal elevations, where mud and sand flat habitat predominate. The prominent diet components of juvenile salmon in both wetlands and unvegetated shallow-water habitats are the tube-dwelling benthic amphipods *Corophium* spp.

Comparable information for estuarine-dependent species and life history types such as ocean-type chinook in the Columbia River estuary is extremely limited. Data characterizing salmonid distribution and ecology in the estuary are biased by the

concentrated effort on stream-type salmonid species and life histories. Although limited data illustrate that the seaward migration rate of subyearling chinook decreases markedly as individuals approach the estuary, no such slowing of migration is shown for stream-type and larger (particularly hatchery-reared) chinook. Thus, large yearling chinook may be less likely to rear in the estuary for extended periods compared with smaller subyearling migrants (Bottom and Jones 1990).

Information about the diet composition of juvenile salmon in the Columbia River estuary is also biased by the predominance of large, stream-type fish in the historical collections. However, the comprehensive collections during investigations by the Columbia River Estuary Data Development Program (CREDDP) in 1980-1981 indicated that both subyearling and yearling chinook salmon in the tidal fluvial and estuarine mixing region of the estuary preyed extensively on invertebrates from shallow-water habitats (McCabe et al. 1986, Bottom and Jones 1990). *Corophium salmonis* tended to be the most prominent prey item and to a lesser extent the congener, *C. spinicorne*, insects (undifferentiated), and the estuarine mysid *Neomysis mercedis*. Planktonic organisms were important food items only in the summer (August) when freshwater cladocerans (*Daphnia* spp.) produced upriver dominated the diet of subyearling chinook.

In no case in the comprehensive CREDDP dataset was there any indication that juvenile chinook (nor coho or steelhead) were utilizing planktonic copepods (e.g., calanoids) produced within the estuary. An important distinction in the apparent[1] prey selection by juvenile salmon is that prey production during peak salmonid occupation of the estuary is largely derived from shallow-water (*Corophium* spp.) and vegetated habitats (insects), while other periods are supported predominantly by pelagic zooplankton produced up-river, particularly in the reservoirs (Sherwood et al. 1990).

Losses of emergent marsh and forested wetland habitats in the Columbia River estuary have been substantial and may be a significant factor affecting the capacity of the estuarine habitats to support juvenile salmon. Approximately 121.6 km^2 of the area of tidal marshes (77% decline) and swamps (62% decline) that existed in the estuary prior to 1870 has been lost, and in combination with a 12% loss of deep-water area, contributed to a 12 to 20% reduction in the estuary's tidal prism (Thomas 1983, Sherwood et al. 1990). Approximately 20% of the original estuary area was lost by the diking or filling of tidal marshes and swamps.

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[1] All inferences about habitat and prey utilization of juvenile salmon based on the 1980-1981 CREDDP sampling must be considered "apparent" because that sampling design significantly under-represented shallow-water habitats such as bays, emergent marshes, and forested wetlands, which may be the location of considerable subyearling salmon utilization of the estuary.

In addition to direct loss of estuarine emergent, forested, and other wetland rearing areas, the associated decline in wetland primary production is directly linked to the significant loss of macrodetritus (~15,800 mt carbon year^{-1}, 84%) that historically contributed to the estuarine food web. The loss of macrodetritus input to the estuarine food web has to some degree been supplanted by an increase of almost 31,000 t carbon year^{-1} of microdetritus from upriver sources, principally phytoplankton production from the reservoirs behind dams on the mainstem Columbia River (Sherwood *et al.* 1990).

However, there is evidence that the modern microdetritus-based food web does not directly support the same diversity of salmon life-history types that was present historically because juvenile salmon typically do not utilize calanoid copepod and other pelagic organisms that are supported primarily by epibenthic-pelagic food webs (Bottom and Jones 1990, Sherwood et al. 1990). The spatial distribution of the food web may also be a critical factor in defining conditions important to habitat capacity.

Within the tidal freshwater region of the estuary, juvenile salmon feed primarily on water-column zooplankton that are supported by and to some cases derived from phytoplankton production in the upriver reservoirs, such as cladocerans (e.g., *Daphnia, Sida, Bosmina*) and cyclopoid copepods (Craddock et al. 1976, McCabe et al. 1983). Whereas the macrodetritus food web was historically distributed throughout the lower river and estuary, the microdetritus-based food web is focused in the highly productive but spatially confined region of the estuarine turbidity maximum.

The estuarine turbidity maximum supports trophic pathways through a planktonic-pelagic food web that contributes little in the way of direct prey of juvenile salmon in the estuary (Bottom and Jones 1990). However, the turbidity-based food web there does support calanoid or cyclopoid copepods that are utilized by very abundant forage fishes in the estuary. These forage fishes, such as northern anchovy (*Engraulis mordax*), Pacific herring (*Clupea harengus pallasi*), and longfin smelt (*Spirinchus thaleichthys*) often appear in the diets of salmon in the nearshore ocean. The survival tradeoffs between the immediate feeding requirements of juvenile salmon in the lower river and estuary versus estuarine support of later needs in the nearshore ocean are unknown.

Absolute changes in habitat opportunity for juvenile salmon do not necessarily depict changes in habitat quality or the associated ecological responses. For instance, while the dramatic loss of emergent and forested wetlands in the estuary has impacted the macrodetritus resource, the area of shallows and flats actually increased 7% between 1870 and 1980, which would have provided some additional foraging habitat. This was independently substantiated by Sherwood et al. (1990), who estimated 68.4 x 10^6 m^3 net sediment gain within the estuary between 1868 and 1958. Areas of sediment increase include peripheral bays such as Cathlamet Bay and Grays Bay which had shoaling rates of 0.61 cm yr^{-1} and 0.63 cm yr^{-1}and net volumetric increases of 76.2 x 10^6 m^3 and 19.1 x 10^6 m^3, respectively.

We have no objective means to quantify effects of this habitat shift from emergent and forested wetlands to shallows and flats. However, it is noteworthy that Jones et al. (1990) found that the standing crop of benthic infauna in the protected flats of the estuarine mixing region was more than an order of magnitude higher (2.058 g m^{-2} AFDW (ash free dry weight) than benthic fauna standing crop in any of the other channel and flat habitats (0.098-0.136 g m^{-2} AFDW). Furthermore, Bottom and Jones (1990) documented an increasing trend in stomach fullness in juvenile chinook and coho salmon from the tidal-fluvial region to the bay and estuarine mixing regions of the estuary. Values subsequently declined in the plume and ocean zone. This pattern, which was consistent for many other fish species investigated during the CREDDP studies, should be viewed cautiously because fish sampling was not designed to compare fish feeding intensity or consumption rates in the estuary.

Fish foraging efficiency is limited by prey availability and their capacity to perceive prey; other behavioral constraints, such as innate responses to predation cues, can also influence prey selection (Gerking 1994). In some estuaries, prey resource density or distribution has been shown to limit juvenile salmonid growth (Reimers 1973) as evident from other estuaries. However, there is very little information from which to assess the potential effects of prey resource variability on salmon in the Columbia River estuary.

High turbidities in the upper and middle reaches of the estuary may be an important factor in fish feeding success, although historic turbidity levels have likely decreased with flow regulation (see Chapter 3). Evidence of turbidity effects is suggested by dietary changes among juvenile salmonids sampled at Jones Beach before and after the 18 May 1980 eruption of Mount St. Helens. Following the eruption, benthic amphipods (*Corophium* spp.) in salmonid stomachs were supplanted by insects and cladocerans (McCabe et al. 1981, Emmett 1982, Kirn et al. 1986) suggesting that either benthic amphipods became less available or were not visible during very high turbidities. The specific impacts of these turbidity-induced changes on salmonid growth or survival are impossible to discern after the fact.

Given the fundamental lack of information on absolute growth and variability of juvenile salmon in the estuary (Chapter 6) it is impossible to assess the potential of carrying capacity limitations during juvenile salmonid rearing in the estuary. This is a particularly important gap in our analysis because our conceptual approach to understanding what estuarine conditions potentially limit the production and survival of Columbia River salmon (Chapter 1) questions whether carrying capacity is necessarily an important factor at all.

Non-Indigenous Species

Non-indigenous species have also imposed a prominent, but unassessed change in the modern estuary. Weitkamp (1994) cataloged 16 fish and four invertebrate species that are nonindigenous to the estuary. While the number of non-indigenous plants, invertebrates, and fishes is expanding, no investigations have assessed whether competitive, predatory, or other interactions with non-native species are limiting estuarine growth or survival of juvenile salmon.

Since its introduction into the estuary in 1838, the Asian bivalve, *Corbicula fluminea*, has expanded its distribution, including recently documented occurrences in the lower mainstem reservoirs and the Willamette and tributary basins (Wentz et al. 1998). In the estuary, *C. fluminea* distribution is restricted primarily to tidal freshwater regions, but also extends into brackish habitats, and it occurs at relatively high levels of standing stock (10-100 mg carbon m^{-2}) in protected and unprotected tidal flats, demersal slopes, and marsh and main channels, and as high as 10,000 mg carbon m^{-2} in subsidiary channels (Holton et al. 1984, Simenstad et al. 1984).

In channel habitats, *Corbicula fluminea* commonly occurs in association with important juvenile salmonid prey, including *Corophium* spp., other amphipods, and dipteran (Ceratopogonidae) larvae (McCabe et al. 1997, 1998). Evidence of invasion by the Asian clam (also called the "prosperity clam"!) *Corbicula fluminea* was discovered in North America in 1924, when empty shells were found in the Nanaimo River estuary, British Columbia (Britton 1979, Counts 1981, Britton and Prezant 1986).

It was first found on the banks of the Columbia River in 1938 (Burch 1944); it spread into the lower mid-west and southeastern U.S. by the 1950s, appearing in Florida in the 1960s (McMahon 1983, Counts 1986). Tourists, fishermen, discharges of bilge water from pleasure boats, aquarium hobbyists, migrating waterfowl, and sand and gravel mining operations are all cited as vectors for spreading the clam over these long distances (Heinsohn 1958, Sinclair and Isom 1963, Abbott 1960). While the ecological impacts of the Asian clam are debatable, significant fouling of canals, culverts, and water intakes have cost approximately $1 billion per year (Isom 1986, OTA 1993).

Despite the long history of colonization and expansion in North America, effects of *Corbicula fluminea* on indigenous communities is poorly known (Strayer 1999). At high densities (Eng (1979) reports densities of ~131,000 m^2 in California canals), potential community-level impacts may be significant, including increased competition for space and food with indigenous species (e.g., Boozer and Mirkes 1979, Clarke 1986). Under extreme conditions, high densities could alter estuarine trophic structure just by filtering large volumes of water (Stites et al. 1995), an effect that has been hypothesized for the non-indigenous *Potamocorbula amurensis* in San Francisco Bay (Carlton et al. 1990, Kimmerer et al. 1994).

Cahoon and Owen (1996), however, suggest that their experimentally-measured filtering rates of 1.12-1.78 L day^{-1} for individual *C. fluminea* were too low to control phytoplankton biomass in a North Carolina Lake, but others (e.g., Lauritsen 1986) have found that *C. fluminea* can have a significant effect on riverine phytoplankton biomass and nutrient cycling. The influences of *C. fluminea* in the Columbia River estuary are poorly understood and not easily predicted given differences in suspended particulate matter. In some cases, the role of *C. fluminea* in the estuary may be positive. As found in other nonindigenous systems where it has become established, *C. fluminea* can become a common food item of fish and wildlife (Keup et al. 1963). It is recorded as prey for steelhead (Bottom and Jones 1990) and is a prominent food item for raccoon (*Procyon lotor*) and surf scoter (*Melanitta perspicillata*) in the estuary (Simenstad et al. 1984).

Studies in other regions have indicated that it has little or no effect on native species in undisturbed situations (Isom 1974; Fuller and Imlay 1976; Klippel and Parmalee 1979; Kraemer 1979; Taylor 1980a,b) and may play a significant role in reducing turbidity and restoring submerged aquatic vegetation (Phelps 1994). Given the ambiguity of documented effects from other regions, determining impacts of the well-established *C. fluminea* population in the lower Columbia River and estuary on juvenile salmon would require dedicated scientific studies of benthic community interactions among co-occurring species that are juvenile salmon prey (e.g., *Corophium* spp.) and the broader effects of *Corbicula fluminea* utilization of sediment particulate matter (SPM) or benthic organic matter that may be a limiting resource.

An introduced calanoid copepod, *Pseudodiaptomus inopinus*, also an Asian species, appeared in the estuary after 1980 and has become abundant (Cordell et al. 1992, Cordell and Morrison 1996). Although the copepod could compete with presumed indigenous calanoid copepods (e.g., *Eurytemora affinis*[2]) and and other prey of planktivorous fishes, there is no evidence that the appearance of *P. inopinus* in the estuary or, for that matter, that any potential displacement of *E. affinis* would significantly impact juvenile salmon.

Present data do not suggest that *P. inopinus* has displaced *E. affinis* (Cordell et al. 1992; unpubl., J. Cordell and C. Simenstad, Univ. Wash.) in the Columbia River estuary, but such an effect has been hypothesized in the Sacramento-San Joaquin Delta/San Francisco Bay (Unpubl. data, J. Orsi, California Department of Fish and Game). During the 1980-81 CREDDP fish surveys, calanoid copepods never were prominent in the diets of juvenile salmon but seasonally were the principal class of prey among pelagic fishes such as American shad (*Alosa sapidissima*), longfin smelt, surf smelt (*Hypomesus pretiosus*), whitebait smelt (*Allosmerus elongatus*), Pacific herring, Pacific tomcod (*Microgadus proximus*), threespine stickleback (*Gasterosteus aculeatus*),

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[2] Ironically, the status of *Eurytemora affinis* as an indigenous zooplankter in the Columbia River estuary may also be in doubt (Lee 1999).

shiner perch (*Cymatogaster aggregata*) and English sole (*Pleuronectes* [*Parophrys*] *vetulus*) (Bottom and Jones 1990).

In addition, concentration of both *P. inopinus* and *E. affinis* production in the estuarine turbidity maximum region would suggest that factors controlling their accessibility as prey to visually-feeding fishes (predominantly those in the estuary) will be estuarine circulation processes of advection from the estuarine turbidity maximum to surface waters. Estuarine dynamics supporting particle and zooplankton trapping in the estuarine turbidity maximum have likely increased with river-flow regulation (Jay et al. 1990), suggesting that production of this zooplankton assemblage has been enhanced since at least the mid-1960s, when flow regulation became coordinated throughout the hydropower system. Because the ETM is located in the estuarine mixing region of the estuary, this zooplankton-dominated food web may contribute less to upper river populations of juvenile salmon (but not necessarily those from the estuary's tributary watersheds, such as the Youngs River) that are likely to rear extensively in the tidal-freshwater and brackish regions above the ETM.

At least 16 non-indigenous fishes, such as American shad, common carp (*Cyprinus carpio*) (appearing in the lower Columbia in 1994), banded killifish (*Fundulus diaphanus*), and yellow perch (*Perca flavescens*) are also now common in the estuary. Only the American shad, a clupeid from the Atlantic coast, has reached extraordinary abundance. Shad appeared in the Columbia from fish introduced into the Sacramento River, where they were planted as early as 1871 (Green 1874).

Shad are now a dominant fish in the Columbia River (Wydoski and Whitney 1979). The rate of American shad population increase is impressive and generally encompasses the period since comprehensive flow regulation came into effect (Fig. 5.1). Misitano (1977) reported only one American shad larvae among monthly ichthyoplankton samples collected in 1973, but by 1980, adults passing Bonneville Dam had become sufficiently abundant (>500,000) to be incorporated into the fish passage counts. Passage of adult American shad at Bonneville reached a peak in the early 1990s but have declined progressively since then.

Although American shad are now a prominent member of the lower River and estuarine ecosystem, we do not know whether they have impacted production of indigenous species. In the estuary, they feed primarily on cladocerans (*Daphnia*) and secondarily on calanoid and harpacticoid copepods, *Corophium salmonis*, and the mysid *Neomysis mercedis* (Bottom and Jones 1990), indicating some overlap with juvenile salmonid diets. Shad are prey of white sturgeon (*Acipencer transmontanus*), harbor seal (*Phoca vitulina*) and avifauna, such as Caspian terns.

Deleterious impacts on the estuarine ecosystem, and juvenile salmon in particular, attributed to any of these introduced populations are entirely speculative because there has been no documentation or experimental evidence to establish a potential interference mechanism. We have no direct evidence of competetive interactions or other adverse effects on juvenile salmonids by non-indigenous species such as American shad. There is qualitative evidence that suggests that juvenile salmonids may have higher consumption rates in the central, estuarine turbidity maximum region of the estuary (Bottom and Jones 1990). However, this may be an indirect effect of the estuarine turbidity maximum because the calanoid copepod-dominated food web within that region does not directly support juvenile salmonids.

A possible mechanism for supporting relatively higher salmonid feeding rates in this estuarine region is that the same concentration of heterotrophic production that supports the estuarine turbidity maximum may also enhance production in adjacent shallows and flats; however, this remains an untested hypothesis. However, given the abundance of *Corbicula fluminea* and American shad (peak Bonneville Dam passage counts of 3×10^6 individuals), and the consequences of comparable infestations in other estuaries (e.g., San Francisco Bay-Delta), it is not unreasonable to hypothesize that their consumption rates could significantly modify, rather than simply enhance, the estuarine food web. However, in the absence of scientific evidence of direct competition or resource limitation, this cannot be assumed to be a deleterious effect on juvenile salmonids. In the case of American shad, it seems likely that the recent population explosion is a symptom of changing food webs and other modifications of the estuarine environment rather than a principal factor of salmon decline

Predation

Predation on juvenile salmonids in the estuary by piscivorous fishes, marine mammals, and birds has always been a mortality factor. In many cases, this predation pressure has likely been diminished because of declines of certain predator populations. Studies suggest that juvenile salmon occur infrequently in the diets of some likely predators, such as harbor seals (WDG 1984). However, several potential predator populations have increased significantly in recent decades. Caspian terns and double-crested cormorant colonies have grown to sizable numbers and have been shown to consume significant numbers of outmigrating juvenile salmon.

For example, through 1999, over 94,000 PIT-tag codes have been retrieved from piscivorous bird colonies on artificial dredge material islands in the Columbia River estuary, representing 1.8% of the total number of PIT-tagged fish released since 1987 (USACE 1999). In 1998, PIT-tag codes from 15.8% of Snake River hatchery steelhead and 13.9% of Snake River wild steelhead that were either marked at Lower Granite Dam or detected at Bonneville Dam were recovered on Rice Island. In the same year, tags from, 2.3 and 1.3% of the hatchery and wild Snake River spring/summer chinook
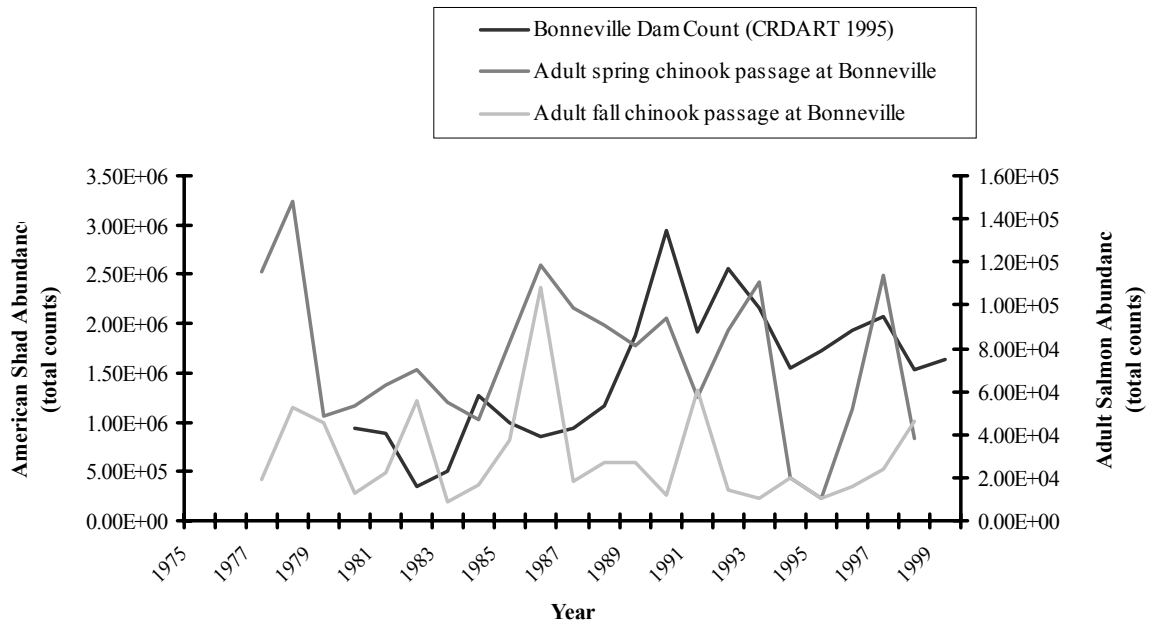
Figure 5.1. Counts of adult American shad and adult spring and fall chinook salmon at
Bonneville Dam, 1975-1999 (CRDART 1995). Chronology: 1885-1886,
first transplants of Atlantic shad into Columbia, Willamette, and Snake
Rivers; 1889, commercial landings reported in Columbia; 1956, American
shad pass McNary Dam; 1995, American shad spawning up to Priest Rapids
Dam on the Columbia River and to Lower Granite Dam on the Snake River.

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SARE draft: Habitat Capacity

salmon, respectively, were detected on Rice Island. In 1999, respective detections were 10.9 and 9.4% for hatchery and wild Snake River steelhead, and 2.3 and 1.3% for hatchery and wild Snake River spring/summer chinook salmon (Steven G. Smith, National Marine Fisheries Service, Seattle, Pers. commun., April 2000; Ryan et al. in press). Because the ratio of PIT tags deposited over water and non-nesting land sites to those deposited on nesting sites is unknown, the actual mortality rate estimates from PIT-tag recoveries is uncertain. However, estimates based on consumption rates and bioenergetic needs to maintain Caspian tern chick growth and health leads to estimates greater than 10 million outmigrating juvenile salmon consumed in the estuary (Roby et al. 1998).

The mortality rates associated with this predation constitute a potential limiting factor on juvenile salmon survival in the lower river and estuary. Of interest, however, is preliminary PIT tags recoveries from the tern colony at Rice island indicating that steelhead smolts were consumed in greater proportion to availability than other salmonid species, and that juvenile salmonids of hatchery origin were consumed in greater proportion to availability than wild smolts (Roby 1998).

Summary and Recommendations

The most significant changes to the capacity of the Columbia River estuary to support juvenile salmon are likely the results of habitat loss. Support of the natural, macrodetritus-based estuarine food web has been significantly diminished by historical diking and filling of 121.6 km^2 of emergent marsh and tidal wetland habitat. Expansion of shallows and flats throughout the estuary, as well as reduction in the spring freshet energy, may have compensated to an unknown degree by promoting productive shallow water habitat. Concurrent changes to the estuary, especially increases in the prominence of non-indigenous species and predators, may have also affected the estuary's capacity to sustain juvenile salmon of diverse life-history types. Yet there is no scientific evidence substantiating or refuting these speculations.

Given the present scientific information, we draw the following conclusions:

1) Habitat loss is well documented in the lower portion of estuary but is unknown for the tidal-fluvial region. The effects on the carrying capacity of the estuary to support salmon are unknown.

2) Foraging and refuge habitat for salmon has been lost, and peripheral wetlands that are among the most critical off-channel rearing areas may have been most impacted; however, because subyearling, ocean-type salmon that utilize these habitats also appear to have declined, the estuary's rearing capacity presently may not be limiting. Nonetheless, recovery of those salmon life histories that depend on shallow-water rearing habitat will require restoration of peripheral estuarine wetlands.

3) Habitat loss implies qualitative change in food web pathways since we have no evidence to suggest that the ETM-based food web supplants the former macrodetritus-based food web. The cumulative effects of such change on juvenile salmon remain uncertain.

4) Non-indigenous species have assumed an increasingly prominent role in the estuarine biotic community and food web. Yet the impacts on juvenile salmon are speculative. Indirect effects, such as those imposed by increased filtering capacity of *Corbicula fluminea*, may be the most identifiable impacts.

5) We have no data to evaluate potential impacts on juvenile salmon of the well-established *Corbicula fluminea* population in the lower Columbia River and estuary. Understanding the significance and scale of *Corbicula fluminea* effects on the estuarine ecosystem will require scientific studies of benthic community interactions among co-occurring salmonid prey species (e.g., *Corophium* spp.) and *Corbicula fluminea* utilization of suspended or benthic organic matter, which may be a limiting resource.

6) Predation of salmon may have increased artificially, due principally to indirect enhancements of predator populations or distributions by dredged material disposal practices and hatchery operations rather than due to river flow regulation. Given that salmonids probably evolved in the presence of even higher predator populations than at present, it is unlikely that natural predation rates and temporal and spatial distributions of predators would be the sole long-term limiting factor.

7) A fundamental lack of information on absolute growth and variability of juvenile salmon in the estuary (Chapter 6) prevents any reliable interpretation of carrying capacity limitations at present or restored population levels. Precise estimates of growth are needed from juvenile salmon of different life-history types corresponding to a range of residence times in the estuary. Approaches that utilize existing or new mark and recapture designs, as well as new techniques such as DNA and Sr/Ca ratios, will be required to effectively obtain individual growth measurements.

6. CHANGE IN JUVENILE SALMON LIFE HISTORY, GROWTH, AND ESTUARINE RESIDENCE

Introduction

Approach and Objectives

All juvenile salmon use the Columbia River estuary as a conduit to the ocean or for rearing habitat during that transition. The patterns of estuarine use by chinook salmon are an aggregate measure of the biological characteristics of all populations throughout the river basin and of the rearing capacity of the estuary itself. Diversity of rearing behaviors may be apparent, for example, by the variation in sizes of individuals collected in the estuary, the times of estuarine entry, and duration of estuarine residence.

In this chapter, we examine evidence for change in life-history diversity that may determine the relative capacity of the estuary to support juvenile chinook salmon. We review whether available data are adequate to evaluate the importance of the Columbia River estuary as a rearing environment for young salmon, to compare historical and contemporary rearing behaviors and growth, and to interpret effects of development and other activities (upstream and in the estuary) on estuarine life histories and performance.

We focus our analysis on chinook salmon for both biological and practical reasons. From a biological perspective, chinook salmon exhibit the greatest variety of rearing behaviors, and therefore, may be the most sensitive indicators of life-history change in the Columbia River Basin. Furthermore, because they are the most estuarine dependent of salmonid species (Healey 1982), chinook salmon offer the best example to evaluate changes in rearing conditions of the estuary. From a practical view, there are simply few data available to assess effects of estuarine habitat change on other salmonid species. While information about chinook salmon in the estuary is sparse, for most other species, it simply does not exist. If the data are not sufficient to evaluate effects of anthropogenic changes on estuarine rearing chinook, we most certainly will be unable to do so for the remaining salmonid species.

Our analysis of chinook salmon is organized in three parts. We begin by reconstructing and classifying historical juvenile life histories from Rich's (1920) survey, the first detailed evaluation of chinook salmon life histories in the Columbia River Basin. These results provide a snapshot of the diversity of juvenile life histories that existed before hydropower development and other activities had substantially modified the river system. We then re-analyze Rich's data to describe historical residence times and size variations of chinook salmon migrants upriver and in the estuary. Finally, in the third part of our analysis, we contrast Rich's results with modern surveys of estuarine residence times and size characteristics to evaluate potential changes in chinook salmon life histories.

Data Sources and Methods for Life-history Analysis

We reviewed published and unpublished data for wild chinook salmon in the Columbia River Basin. The principal sources we used to evaluate past and present estuarine rearing patterns are briefly described below.

Historical Life Histories and Growth--Rich's (1920) investigation of juvenile chinook life history was conducted from 1914 to 1916. During this period, Rich sampled juvenile chinook salmon throughout the estuary with a 100-foot beach seine (one-half-inch mesh in the wings and one-quarter-inch mesh in the pocket) and to a lesser degree, by "hook and line" (Fig. 6.1). Rich did not report catch per effort, thereby limiting our ability to estimate abundance or determine seasonal trends. However, he did describe fork lengths (FL) of juvenile fish and analyzed scale samples to determine migration patterns and growth. We further analyzed his data to assess early life-history attributes of subyearling chinook salmon in the estuary including the duration of their estuarine residency (Table 6.1).

The scale patterns described by Rich (1920) allowed interpretations of life-history attributes of juvenile chinook salmon. Gilbert (1913) was the first to recognize the relationship between scale patterns and anadromous salmon rearing behavior. Gilbert noted variations in the thickness and bandwidth of scale circuli, which indicated changes in environmental conditions. An increase in growth rate was noted by a widening of the circuli bandwidth, whereas a narrowing of the bands formed a pronounced "check" on the scales denoting lower growth rates. Gilbert and Rich identified incremental increases in circuli width that coincided with successive periods of rearing in freshwater, estuarine, and marine environments. Similar scale methodology has been used more recently to interpret juvenile rearing behaviors and their contribution to adult chinook salmon returns in the Rogue (Schluchter and Lichatowich 1976, 1977) and Sixes Rivers (Reimers 1973) in Oregon.

Rich (1920) identified and interpreted four patterns associated with check marks (narrowing of the circuli rings) on juvenile chinook salmon scales based on the methods of Gilbert (1913): no check, a primary check, an intermediate check, or a first-year annulus. If no check mark was observed then the juvenile had presumably reared only in its natal stream. A primary check formed when a juvenile migrated and reared in a river system downstream from its natal stream. The preceding growth was similar to the growth succeeding the check. An intermediate check indicated migration into the estuary and was associated with a notably higher growth rate compared to freshwater growth but was significantly less than that observed in the ocean (Gilbert 1913, Rich 1920). A first-year annulus was first observed on scale margins of fish sampled in October and was not discernable from an intermediate or primary check due to the similar growth rates with the onset of winter (Fig. 6.2).
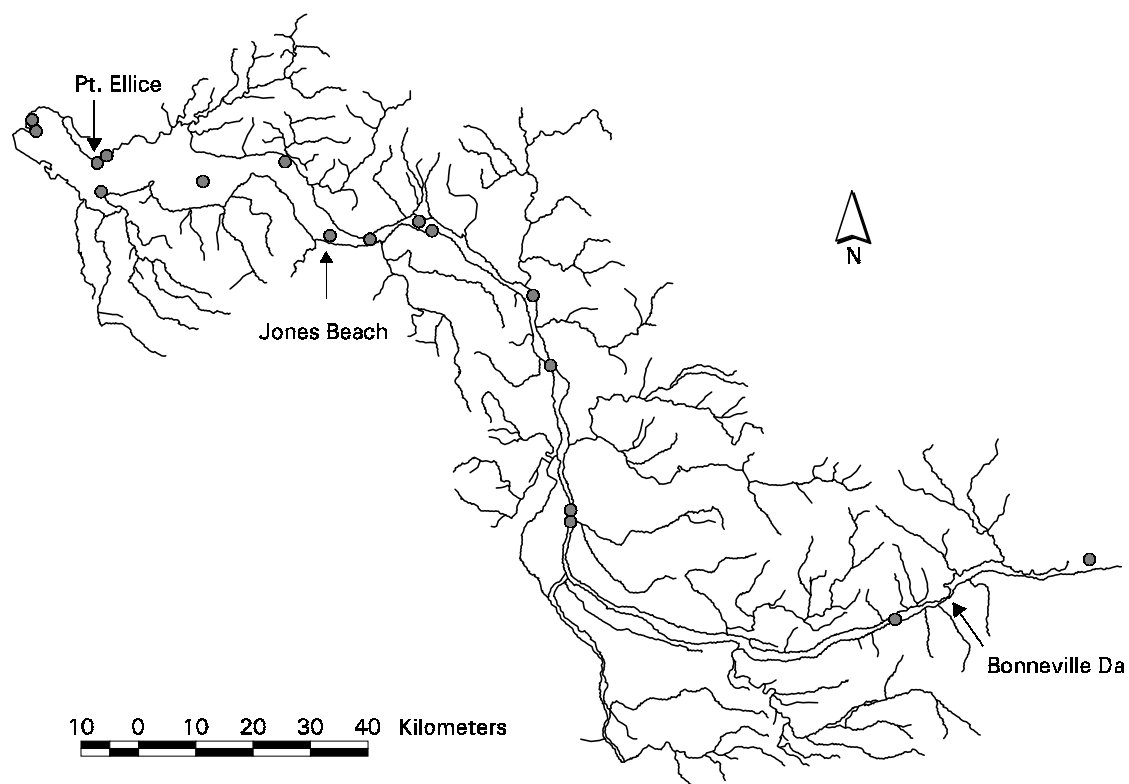
Figure 6.1. The Columbia River estuary and tributaries, with sites sampled from 1914 to 1916 marked by circles (Rich 1920).

Table 6.1 Summary Table for 1914-1916 sampling effort and subyearling and yearling chinook salmon attributes interpreted from scale patterns.

							No circuli marks			
Date	Site	Gear Type	Number of Fish (n)	Number <= 60 mm	Number > 60 mm	Total with Estuarine Growth (%)	n	Percent of sample	FL range (mm)	Mean FL (mm)
Subyearling										
17 Sep 1914	Ilwaco, WA under cannery	Hook and Line	35	0	35	80	7	20	116-120	118
24-27 Oct 1914	Ilwaco, WA under cannery	Beach Seine	100	0	100	94	3	3	121-125	123
7 Nov 1914	Astoria, OR	Hook and Line	6	0	6	100	0	-	-	-
16 Oct 1915	Point Ellice	Beach Seine	119	0	119	24	30	25	96-125	113
17 Oct 1915	Astoria, under cannery	Hook and Line	61	0	61	70	7	11	106-155	125
19 Nov 1915	Warrendale, OR	Beach Seine	7	0	7	-	6	86	91-95	93
3 Dec-8 Dec 1915	Lower Columbia River, Willamette to Astoria	Beach Seine	39	1	39	54	18	44	31-95	93 *
31 Mar-Apr 2 1916	Mayger, OR, Grims Island, Sand Island and Point Ellice	Beach Seine	102	102	0	-	102	100	31-50	39
13 Apr 1916	Cottonwood and Deer Island	Beach Seine	26	24	2	-	26	100	31-70	43.2
10 May 1916	Grims and Puget Island	Beach Seine	218	166	52	-	218	100	31-100	52.7
11 May 1916	Point Ellice and Tenasillihee Island	Beach Seine	103	100	3	-	103	100	31-85	46.8
13 Jun 1916	Within mouth of small creek near Point Ellice	Beach Seine	36	33	3	-	36	100	36-70	47.7
12 Jun-13 Jun 1916	Point Ellice	Beach Seine	96	7	89	17	80	83	51-105	75.7
19 Jul 1916	Point Ellice	Beach Seine	166	1	165	70	50	30	56-115	89.9
12 Aug & 26 Aug 1916	Point Ellice	Beach Seine	64	1	63	58	27	42	46-110	87.8
15 Sep 1916	Grims Island	Beach Seine	69	1	68	4	66	96	56-90	74
Totals			1247	436	812		779			-
Yearling										
31 Mar-2 Apr 1916	Lower Columbia River	Beach Seine	47	-	-	72	0	-	-	-
13 Apr 1916	Deer and Cottonwood Islands	Beach Seine	22	-	-	77	0	-	-	-
10 May 1916	Grims Island	Beach Seine	39	-	-	100	0	-	-	-
11 May 1916	Point Ellice and Tenasillihee Island	Beach Seine	10	-	-	100	0	-	-	-
Subtotals			118				0			
Totals			1,365				779			

Table 6.1. Continued.

Date	n	Percent of sample	FL at formation of check	Growth in fluvial environment (%)	Number of fish (n)	Number of fish (n)	FL Range at onset (mm)	Fluvial growth (%)	FL range (mm)	Mean FL (mm)	FL range at onset (mm)	Growth range (mm)	Mean growth (mm)	Growth range (%)	Mean growth (%)
		Primary check only (without estuarine growth)				Estuarine Growth *(second year growth by October)*									
						Primary check									
Subyearling															
17 Sep 1914	-	-	-	-	28	-	-	-	101-155	123.5	70-118	15-55	30.4	11.3-35.9	23.6
24-27 Oct 1914	3	100	49.7	60	94	36	38-88	-	106-205	148.3	88-123	20-82.5	48.1	16.9-42.7	29.9
7 Nov 1914	0	-	-	-	6	5	48.8	-	131-135	133	111.6	21.4	21.4	16.1	16.1
16 Oct 1915	60	67	47.1- 88.0	40.5-60.5	29	17	43-55	-	96-135	112.1	85.5-118	10-30	17.9	7.8-24.4	15.5
17 Oct 1915	11	30	40.5-65.5	42.0-67.1	43	33	43-63	-	96-180	130.9	78-123	5-60	27.0	5.1-33.7	19.6
19 Nov 1915	1	14	*no data*	*no data*	-	-	-	-	---	-	--	---	-	---	-
3 Dec-8 Dec 1915	0	-	-	-	21	0	-	-	76-130	91.5	63-98	10.0-35.0	22.0	12.8-27.3	22.0
31 Mar-Apr 2 1916	-	-	-	-	-	-	-	-	-	-	--	-	-	--	-
13 Apr 1916	-	-	-	-	-	-	-	-		-	--	-	-	--	-
10 May 1916	-	-	-	-	-	-	-	-	-	-	--	-	-	--	-
11 May 1916	-	-	-	-	-	-	-	-	-	-	--	-	-	-	-
13 Jun 1916	-	-	-	-	-	-	-	-	-	-		-	-	-	-
12 Jun-13 Jun 1916	-	-	-	-	16	-	-	-	66-95	83	49-63	19.5-38.4	27.7	28.7-43.6	34.1
19 Jul 1916	-	-	-	-	116	-	-	-	61-130	93.3	38-77	12.5-85	40.0	19.8-66.4	41.5
12 Aug & 26 Aug 1916	-	-	-	-	37	-	-	-	76-125	98.4	48-81	30-50	40.6	31.8-52.6	40.6
15 Sep 1916	-	-	-	-	3	-	-	-	86-90	88	39 -39	48.7-48.7	48.7	55.3	55.3
Totals	75				393	91									
Yearling															
31 Mar-2 Apr 1916					34	4			86-115	96.4	69.5-85.5	18.5-28	22.5	19.5-27.2	22.5
13 Apr 1916	-	-	-	-	17	0	-	-	106-110	108	87.2	20.8	21.8	19.3	19.3
10 May 1916	-	-	-	-	39	0	-	-	81-125	103	53-100.5	21.7-43.4	28.8	18.3-36.8	28.2
11 May 1916	-	-	-	-	10	3	-	-	106-110	108	73.7	34.3	34.3	31.8	31.8
Subtotals	0	-	-	-	100	7	-	-							
Totals	75				493	98									

Figure 6.2. Example of subyearling chinook salmon scale patterns analyzed by Rich (1920). Both scales were collected at Point Ellice on October 16, 1915. Scale on the left depicts natal stream growth rings, an intermediate check mark, and estuarine growth (starting at g) on the outer margin. Scale on the right depicts a fall migrant with natal stream rearing and the start of winter band on the outer margin (reproduced from Rich 1920).

Rich (1920) mathematically correlated the sizes of juveniles at the time of sampling with patterns on their scales to interpret rearing behavior, which we used to classify life-history attributes. Rich used direct proportionality, a method developed by Dahl (1911), to back-calculate the fork lengths of fish associated with various life-history events interpreted on the scales. The ratio of the distance between two points on a scale is proportional to the fork length at capture and the fork length at the time of formation of the mark. For instance, Rich back-calculated the size at estuary entrance for juvenile chinook based on the fork length at capture and the distance on the scale from the margin to the intermediate check. Unfortunately, Rich reported his results as averages for each (5 mm) size class, which leaves no record of variability within each class.

Because Rich (1920) rarely sampled each site more than once during the three years of his survey, we are unable to compare trends in population abundance, size, or life-history characteristics throughout the estuary. However, he collected a consistent series of samples from 11 May to 26 August 1916 at Point Ellice, a site on the north shore at RKm 19. These data sets provide a comparative time series of chinook life-history attributes during the summer and early fall (Fig. 6.3). Rich combined two beach seine sets in May, one from Tenasillihee Island, approximately 38 km upriver, with those from Point Ellice, since he observed no significant differences in scale patterns between the sites. We used Rich's back-calculations of fish size to estimate the total growth from estuary entrance until their capture at Point Ellice. As further described in our results, we applied literature values for estuarine growth rates of chinook salmon to estimate residence times for juveniles collected at Point Ellice. We also examined the size structure of the subyearling chinook population. Although clearly not representative of all habitats or salmon life histories in the estuary, the Point Ellice results provide the only consistent data series for interpreting sizes at estuary entrance or growth rates of juvenile chinook before the Columbia River Basin and estuary were substantially altered in the 1930s.

Contemporary Life Histories and Size Characteristics--We know of no contemporary estuarine surveys or scale analyses of wild chinook salmon directly comparable to Rich (1920). Consequently, we cannot quantitatively assess changes in estuarine life histories and residency of chinook salmon since 1916. No contemporary growth rates for salmon exist for the Columbia River estuary. However, several recent surveys in the estuary and in tributary streams allow us to qualitatively compare historical and contemporary life-history attributes and size structure. Reimers and Loeffel (1967) report the timing and duration of migration into the estuary from 11 tributaries of the lower Columbia River, from which we extracted examples of the diverse migration patterns of wild juveniles within a sub-basin. McIsaac (1990) compared migration timing and adult contribution between wild and hatchery-reared subyearling chinook salmon in the Lewis River, Washington. We further analyzed the Lewis River data to describe recent abundance patterns and timing of salmon migrations to the estuary.

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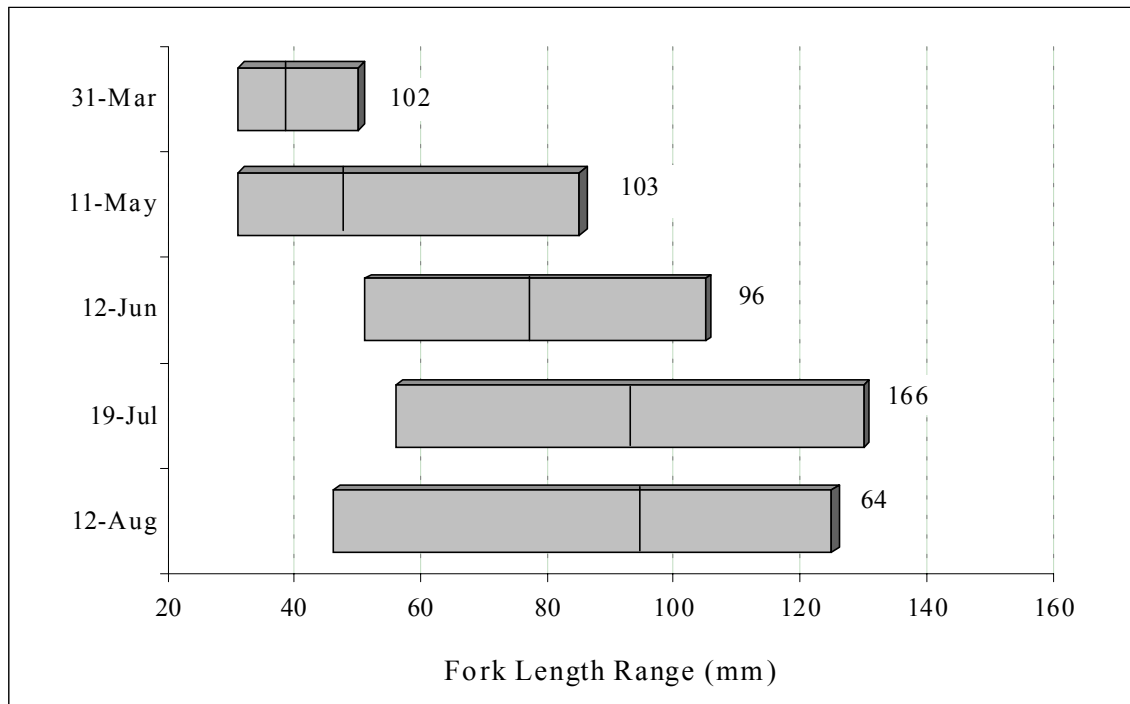
Figure 6.3. Range of subyearling chinook salmon fork lengths collected at Point Ellice by Rich (1920) from March to August 1916. Mean fork length denoted by vertical line.

To compare recent size characteristics of juvenile salmon with the results of Rich (1920), we analyzed a variety of published and unpublished records from miscellaneous surveys conducted near Point Ellice. The most comparable data were from Dawley et al. (personal communication; 1986), who used similar gear and sampled habitat similar to Rich during a 1966 beach seine survey at Megler, approximately 1.5 km downstream from Point Ellice. Dawley et al. (1986) used a 95-m beach seine with variable mesh in the wings (one-half-inch to three-quarter-inch mesh) and one-quarter-inch mesh in the pocket. Because hatchery fish were not marked in the 1960s, we are unable to separate wild from hatchery subyearlings in these records.

More recent survey results comparable to Rich (1920) are available from the Columbia River Estuary Data Development Program (CREDDP), a comprehensive ecological survey of the estuary below Puget Island. CREDDP inventoried fish assemblages monthly using a variety of gear types at 63 stations from January 1980 to July 1981. Analyses of salmonid catches from the CREDDP survey are presented in Durkin (1982), Bottom et al. (1984), and McCabe et al. (1986). We analyzed size characteristics of juvenile chinook from unpublished purse seine and trawl data collected in the north channel (RKm 18.9 to 19.4) during CREDDP and additional 1980 purse seine data collected at McGowan (RKm 16) and reported in Dawley et al. (1985). In contrast to the 1966 survey data (described above), a proportion of the fish released from Columbia River hatcheries were marked so that some of the hatchery fish are identifiable in the data. However, unmarked chinook salmon represent a mixture of hatchery and wild juveniles.

A majority of the present-day information about the estuarine life history and movements of chinook salmon is derived from migration rate and survival studies of marked hatchery fish. NMFS has been monitoring chinook salmon at Jones Beach (RKm 75) from 1966 to 1972, 1977 to 1983, and 1995 to the present (Dawley et al. 1986; Ledgerwood et al. 1997). We selected tag groups of hatchery fish collected during the Jones Beach surveys prior to 1983 to analyze population size structure, timing, and abundance of migrant hatchery chinook salmon.

Salmon were collected at Jones Beach primarily by beach and purse seine, with subyearling salmon concentrated in the beach seine collections (Dawley et al. 1986). Approximately 2.3 to 6.5% of all fish recovered at Jones Beach were tagged or fin clipped. The vast majority of the marked fish had coded-wire tags bearing numbers unique to a particular hatchery or study. This marking method is used to track groups of fish but not individuals. Over 90% of these marked fish were hatchery-reared juveniles. The remaining unmarked fish were of either wild or hatchery origin(Dawley et al. 1986).

Life-History Reconstruction

Rich's (1920) historical survey of juvenile chinook salmon and their scale patterns revealed evidence of stream-type and at least five forms of ocean-type juveniles (Table 6.2). The characteristics of each stream and ocean life-history type are described below.

Stream-Type Juveniles

Stream-type juvenile chinook salmon migrate to the ocean as yearlings (age 1) and were present in late March to early May estuary samples. Fork lengths of yearling fish ranged from 81 to 125 mm. Rich (1920) was unable to determine whether the yearlings he collected had previously reared in a fluvial (riverine) or estuarine environment due to the similarity in the annulus and intermediate check mark and preceding growth. However, he was confident that most yearlings left the estuary for the ocean by June since they were absent in all subsequent samples.

Ocean-Type Juveniles

Ocean-type juvenile chinook salmon, which migrate to sea during their first year, vary considerably in their early life histories. During Rich's (1920) surveys, ocean-type juveniles were substantially more abundant than stream-type juveniles in all samples where both were present (Fig. 6.4). Rich classified the juveniles according to the presence and absence of scale patterns and discussed the mechanisms responsible for the observed differences. We further classified ocean-type juveniles into a series of subgroups based on their size, rearing behavior, and seasonal time of capture in the estuary (Table 6.2). Since the data from Rich are inadequate to conclude the time at which the juveniles entered the ocean, the following interpretations of ocean-type life histories are presented as hypotheses.

Fry--Chinook salmon fry (defined here as fish less than 60 mm FL) arrived in the estuary over an extended period and were distributed throughout tidewater. Fry were consistently collected in the marine, brackish, tidal-fluvial regions of the estuary from late March through September 1916, and in December 1915 (Fig. 6.5). Fry less than 50 mm FL comprised 25% of all the juveniles Rich (1920) sampled in the Columbia River estuary. Fry collected in the estuary were as small as 31 mm FL. All fish collected from 31 March to 2 April 1916 were less than 50 mm FL range (n = 102). Most of these fish were collected at Sand Island (RKm ~7) and Point Ellice (RKm ~19). Almost half (45%) of the fry in this sample showed evidence of riverine or estuarine growth on their scales. Successive fry collections are described in Table 6.3. August and September samples confirmed a late fry migration into the estuary. Several smaller subyearlings in the 40 to 70 mm FL range were found in brackish waters at Point Ellice in mid-August and in the tidal-fluvial region as late as September (Table 6.3).

Table 6.2. Interpretation of juvenile chinook life history from scale analyses
(Rich 1920).

Scale structure	Life-history type collected	Rearing behavior	Percent of total
No check marks	Fry	Short rearing period in natal stream.	33
No check marks	Fingerling *Smolts and recent arrivals*	Reared in natal system. Migrated immediately as a fry to fluvial system following emergence.	28
Primary check only	Fingerling *Fluvial-rearing*	Fluvial-rearing as fry. Fluvial-rearing as fingerling.	6
Intermediate check only *second-year growth if check formed in winter*	Fingerling *Estuarine-rearing*	Estuarine-rearing as fry. Estuarine rearing as fingerling.	25
Primary and intermediate checks present	Fingerling *Fluvial and estuarine-rearing*	Fluvial-rearing and estuarine-rearing. *Indistinguishable from primary and annuli combination if intermediate check formed in early winter*.	8
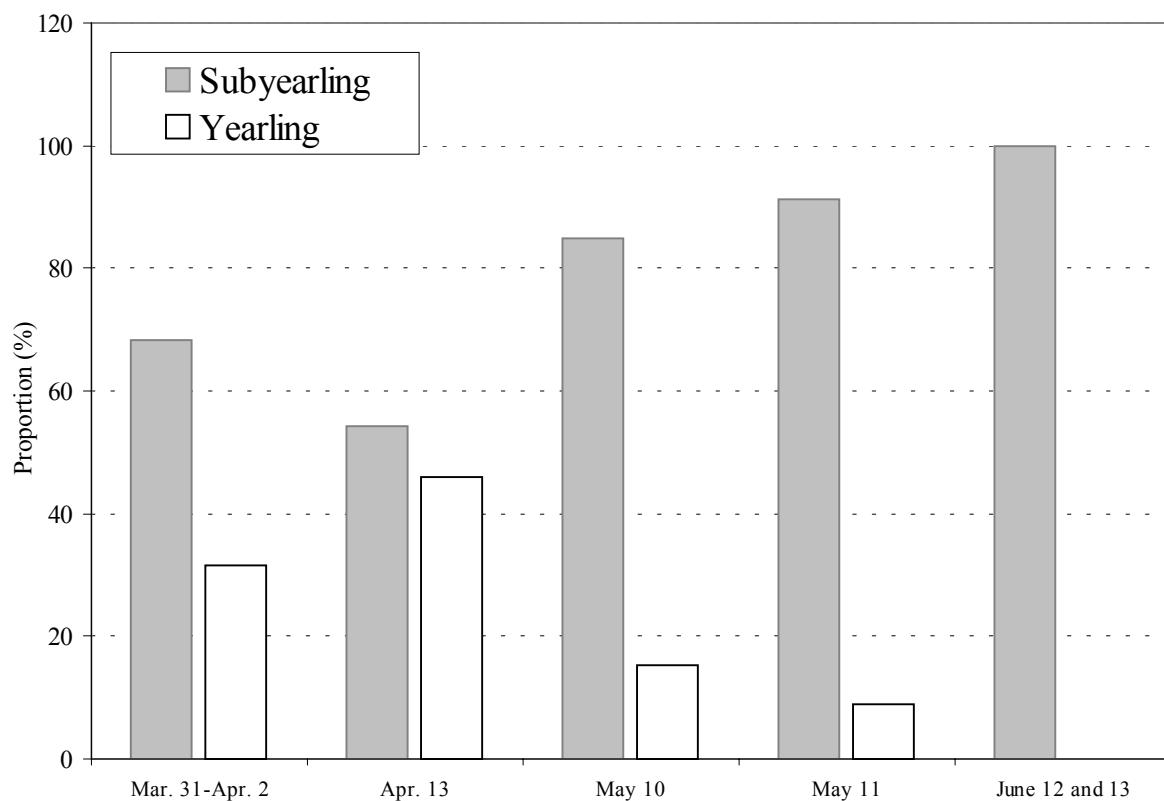
Figure 6.4. Proportion of subyearling and yearling chinook salmon juveniles collected concurrently in 1916 estuary collections by Rich (1920). Yearlings did not appear in samples after May.
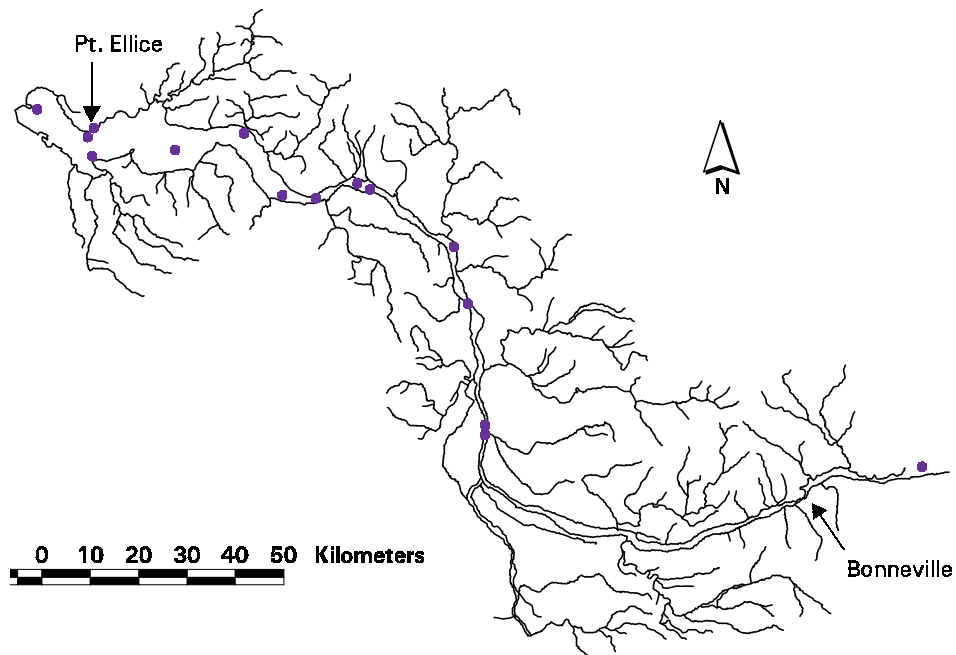
Figure 6.5. Columbia River estuary collection sites (indicated by dots) where fry
(<60 mm) were sampled in December 1915 and from March to September
1916 (Rich 1920).

Table 6.3. Fry migrant attributes (Rich 1920).

	3 Dec 1915	31 Mar-1 Apr 1916	13 Apr 1916	10 May 1916	11 May 1916	25 May 1916	12-13 Jun 1916	19 Jul 1916	12 & 26 Aug 1916	15 Sep 1916
Location	Upper and middle	Middle and lower	Cottonwood and Deer Isl.	Crandall's seining ground and Puget Island	Point Ellice and Tenasillihee Island	Near mouth of Little White Salmon	Point Ellice	Point Ellice	Point Ellice	Grim's Island
Brackish or tidal-fluvial (TF)	TF	TF and brackish	TF	TF	TF and brackish	Freshwater	Brackish	Brackish	Brackish	TF
FL range (mm)	35.5	31-50	31-60	31-60	32-60	36-60	51-60	56-60	46-50	56-60
Fry less than 50 mm (%)	100	100	88	69	73	75	0	0	100	0
Number of fry smaller than 60 mm	1	102	24	166	100	23	7	1	1	1
Percentage of collection less than 60 mm	6	100	92	76	97	96	9	2	4	1.5
Number of circuli formed (fry < 60 mm)	0	1.5-3.0	2.0-5.0	1.3-6.2	1.6-6.2	1.5-6.7	4.0-7.0	9	4	13
Number of migrants smaller than 70 mm	1	102	26	191	102	25	26	6	4	22

Rich (1920) contended that the recent arrivals below 70 mm might have originated from stream systems with conditions that produced relatively low growth rates. Alternatively, the fry may have originated from upper Columbia River tributary streams that coincided with a later emergence time. The possibility of later emergence times was supported by more recent studies in the Lewis River, which provided evidence that salmon fry continued to emerge from the gravel for at least a 3.5-month period (April to August) (Reimers and Loeffel 1967, McIsaac 1990). While the number of fry arriving in the fall is extremely small, the data indicated a large range in the emergence times and that at least some fry arrived in the estuary late in the season.

Fry that did not rear in the lower estuary for an extended period may have headed directly seaward. The presence and survival of individuals of this life-history type are supported by typical ocean-type scales with a pattern for ocean-migrant fry, which Rich (1928) found among returning adults sampled in 1923-1924.

Fingerlings--Subyearling chinook salmon greater than 60 mm FL (fingerlings) were present at lower and middle estuary sampling sites from April to December 1916. Fingerlings first appeared in samples collected on 13 April and 11 May in the upper estuary, although they were less abundant than fry. The collection of 12-13 June showed an increase in fingerling abundance in the middle estuary.

We identified four distinct types of fingerling life histories from the scale patterns documented by Rich (1920):

1)   *Recent arrivals*. Rich (1920) interpreted fish scales without checks as subyearlings that had recently migrated to the estuary and had not yet had an opportunity to feed after leaving their natal stream. Approximately 63% of the fingerlings collected had scales that did not possess check marks. Without specific data from Rich, we must assume that the recent arrivals could have included both smolts headed seaward and fingerlings bound for estuarine rearing habitats.

2)   *Estuarine rearing*. Fingerlings with only an intermediate scale check (14% of total collection) had reared for a short period in their natal stream and migrated to the estuary to rear. Fingerlings of this type, which were present in the estuary from June through September, arrived as either fry or fingerlings. For instance, subyearlings collected from June to August 1916 at Point Ellice ranged from 61 to 130 mm FL and, based on back-calculations from scale measurements, had arrived in the estuary at 38 to 80.5 mm FL. All subyearlings with evidence of estuarine growth were greater than 60 mm FL at capture and were on average larger than those lacking estuarine growth in the same collection (Table 6.1). The proportion of subyearlings with evidence of estuarine growth varied by month, but peaked at 70% in the mid-July sample. The fork length at arrival in the estuary was highly variable between sample sites and months. An unusual collection in September 1914 at Ilwaco, Washington, under a cannery yielded

subyearlings that had entered the estuary at 70 to 118 mm FL. Rich (1920) found that these large fish had fed exclusively on the offal discarded by the canneries and may have delayed ocean entry due to optimum feeding opportunities.

3)   *Adfluvial rearing*. Rich (1920) defined fingerlings with only a primary scale check as individuals that had migrated to a lower, larger stream system (adfluvial system) early in their life history, forming the primary check. Fingerlings with only a primary check were first collected in the estuary in October (1914). They constituted 26% of the total 332 fingerlings collected from October to November 1914 and October to December 1915.

All subyearlings of this life-history type were 95 to 150 mm FL. The primary check formed when individuals were 40.5 to 88 mm FL indicating that some of the juveniles had migrated to a lower stream system as fry, while the others had remained to rear in the natal stream for an extended period prior to outmigration. The amount of adfluvial growth was equal to or greater than their natal-stream growth, based on the length of the anterior scale radius. However, the lack of widening of the bands precluded classification as estuarine growth. Therefore, the primary check indicated that the subyearlings had migrated from their natal stream to rear in a larger stream system before arriving in the estuary.

4)   *Adfluvial rearing with an additional check mark*. Fall samples (October to December 1914 and 1915) were composed of larger subyearlings (90-205 mm FL) with two check marks signifying that they had reared for a short period in the riverine, and potentially, the estuarine environment. Primary or intermediate checks that formed in the late fall and winter were not distinguishable from annuli. Therefore, Rich (1920) classified the outermost check regardless of what point in the fish's life history that the mark formed as intermediate, but he recognized that it may have been an annulus. These fingerlings had migrated to a larger stream system (forming the primary check) and had either reared in the estuary (forming an intermediate check) or laid down an annulus in the river or the estuary. The primary checks were formed at 38 to 88 mm FL, the majority of which were fry indicating formation early in their life history. The subyearlings with both scale checks averaged about the same fork length or larger than the subyearlings without the second check in the same collection. The estimated length at which the intermediate check formed on all the fish was within the last 30 mm of total growth, which means the placement of the intermediate check was relatively recent and does not eliminate the possibility that it was an annulus. All intermediate checks formed in late fall were likely annuli so that subsequent growth on the scales represented second-year growth rather than estuarine growth. Due to the uncertainty of the interpretation of the intermediate check in this case, both scenarios are possible.

Historical Estuarine Residence Times and Performance

Length Characteristics

Rich's (1920) series of fish collections at Point Ellice provide the best data to interpret historical sizes and growth of juvenile chinook salmon within the Columbia River estuary. Although these results are clearly inadequate to characterize estuary-wide rearing patterns or to quantify absolute abundances, the results demonstrate considerable variation in juvenile size classes as might be expected from the diverse life histories that Rich identified based on scale analysis.

Rich's (1920) results indicated that small subyearling chinook salmon (< 60 mm) continued to arrive at Point Ellice from May until August 1916, while the upper size ranges of subyearlings steadily increased (Fig. 6.3). The earliest collection at Point Ellice in May was primarily fry (n = 103) that had recently emerged and migrated to the estuary. Subyearlings in the June and July collections were progressively larger, and the average fork length was significantly greater (P < 0.05) than the previous month. However, the mean and median fork lengths were essentially identical between the July and August collections (P > 0.05), which may reflect the later influx of small fry and fingerlings as well as the continued outmigration of larger smolts to the ocean. The continuous influx of fry and fingerlings of relatively similar size reflects the variability in emergence timing, migration distances, and growth rates among individuals entering the estuary from tributaries throughout the basin.

Estuarine Growth and Residence Times

Rich's (1920) time series of scale samples collected at Point Ellice can be used to estimate the growth of those subyearling chinook that resided in the estuary for an extended period (e.g., showed evidence of an intermediate scale check) (Table 6.4). Of the entire collection, 17% of the subyearlings had evidence of estuarine growth, which accounted for 29 to 44% of their total length at the time of capture. Mean estuarine growth nearly doubled from June to July but remained steady from July to August (Table 6.4). By July, 70% of the subyearlings exhibited estuarine growth, which contributed from 20 to 66% of their total length. The proportion of subyearlings with estuarine growth decreased to 58% in August and accounted for a third to a half of the total body length of these fish.

We have no direct measurements of how long individual fish remained in the estuary. To approximate residence times for all subyearlings with an intermediate scale check, we applied literature values for growth rates to total growth in the estuary as estimated from scale analyses (Table 6.5). For example, Healey (1980, 1991) reported estuarine growth rates from 0.4 to 1.32 mm per day. If we assume an optimistic rate of 1.5 mm per day, then the fish collected at Point Ellice in June that exhibited estuarine growth had remained in the estuary for an average of 18.5 days with a range of 13.0 to 25.6 days.

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Table 6.4. Summary table of chinook subyearlings collected at Point Ellice from May to August 1916. Fork length data from Rich (1920).

	11 May	12-13 June	19 July	12 and 26 August
Mean (mm)	46.8	76.9	92.3	93.9
Median (mm)	48	78.0	93.0	93.0
Range (mm)	31-85	51-105	56-130	46-125
Average Estuarine Growth (mm)	--	27.7	40.0	40.6
Range of growth (mm)	-----	28.7 – 43.6	19.8 – 66.4	31.8 – 52.6
Estimated Residency (days) based on 1.5 mm/day rate	-----	18.5	26.7	27.1
Mean FL difference to previous sample (*t*-test, two-sided P-value)		$P < 0.05$	$P < 0.05$	$P = 0.384$
Median FL difference to previous sample (Mann-Whitney W test, two-sided P-value)		$P < 0.05$	$P < 0.05$	$P = 0.152$

Table 6.5. Estuarine and freshwater growth rates from Pacific Northwest river systems.
Rates are based on changes in average fork length and monitoring of marked
individuals.

Sacramento River Delta (freshwater)	0.86 mm day^{-1}	0.57 to 1.23 mm day^{-1} in 1980	Kjelson et al. 1982
	0.53 mm day^{-1}	0.40 to 0.69 mm day^{-1} in 1981	
Sacramento River Bay	1.01 mm day^{-1}	1980	
Nanaimo River estuary	1.32 mm day^{-1}	(average)	Healey 1980
Fraser River estuary	0.56 mm day^{-1}	1978	Levy and Northcote 1981
	0.39 mm day^{-1}	1979	
Sixes River	0.9 mm day^{-1}	April to June	Reimers 1973
	0.07	June to August	
	0.5 mm day^{-1}	September to November	
Nitinat estuary	0.62 mm day^{-1}		Fedorenki et al. 1986

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By July, the time range increased to 8 to 57 days with an average of 27 days. Residence time values were less variable in August (20 to 33 days) but still averaged about 4 weeks. If we assume a more conservative growth rate of 1 mm per day, estuarine residence times in July and August to the time of capture at Point Ellice averaged approximately 40 days (Table 6.4). The largest fish at the time of collection typically had the most estuarine growth (Fig. 6.6). These same fish had arrived in the estuary at the smaller size classes (Fig. 6.7). Variability within each size class could not be accounted for because Rich (1920) presented the scale analysis as averages by 5-mm size class.

According to the back-calculation results, spring and summer fry migrants (in contrast to fingerling migrants) contributed largely to the estuarine rearing groups collected in June and July. While fry dominated the early spring collections, it is apparent that at least a portion remained and survived to rear in the estuary.

Contemporary Estuarine Residence Times and Performance

Patterns of Abundance

Subyearling chinook salmon populations exhibited a seasonal pattern in abundance but were present in the estuary throughout the year (Bottom et al. 1984, Dawley et al. 1986, McCabe et al. 1986). Peak abundance occurred from May to September when the majority of the subyearlings migrated into the estuary (McCabe et al. 1986). McCabe et al. partitioned subyearling abundance in the estuary by regions above and below Tongue Point and by pelagic and intertidal habitat within each region (Fig. 6.8). In 1980, in the pelagic habitat in the upper estuary, chinook showed a bimodal peak in abundance (May and July); while in the pelagic habitat in the lower estuary, subyearling abundance peaked in July. The bimodal abundance pattern in the upper pelagic habitat may have been influenced by the eruption of Mount St. Helens since that pattern did not occur in 1981. In 1980, abundance in the intertidal habitat peaked in June in both the upper and lower estuary. In 1981, abundances throughout the estuary peaked in the pelagic habitat in July and in the intertidal habitat in June.

In the analysis of Jones Beach seine surveys from 1966 to 1972, Dawley et al. (1986) reported a shift in bimodal peak abundance timing from May and June to late July and early August. However, this shift was not apparent during the same surveys in 1977 to 1983, when the primary peak in abundance occurred in early May or June with smaller but significant peaks later in the summer (Dawley et al. 1985). There were independent peaks in abundance at Jones Beach for particular populations that deviated from the main peaks in the estuary. For instance, abundance of wild subyearling chinook from the Lewis River consistently peaked in July at Jones Beach during a 3-year study (1978-1980) (Dawley et al. 1985). Peak catches at Jones Beach were primarily composed of hatchery-reared fish and were highly correlated with the timing of hatchery releases (Fig. 6.9).
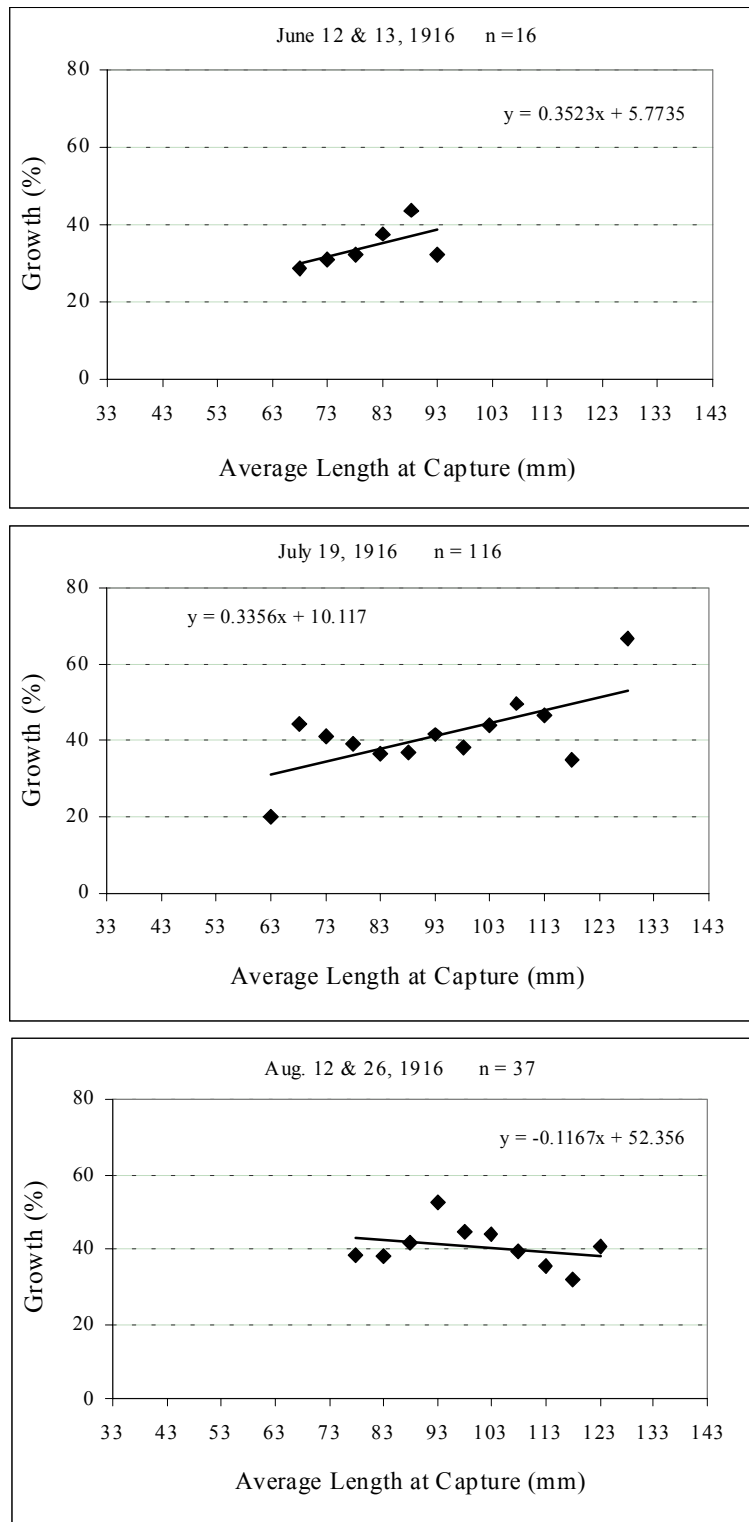
Figure 6.6. Trend lines of subyearling chinook salmon fork length at time of collection
and percent of total length attributed to estuarine growth. All fish collected
at Point Ellice in 1916 (Rich 1920).
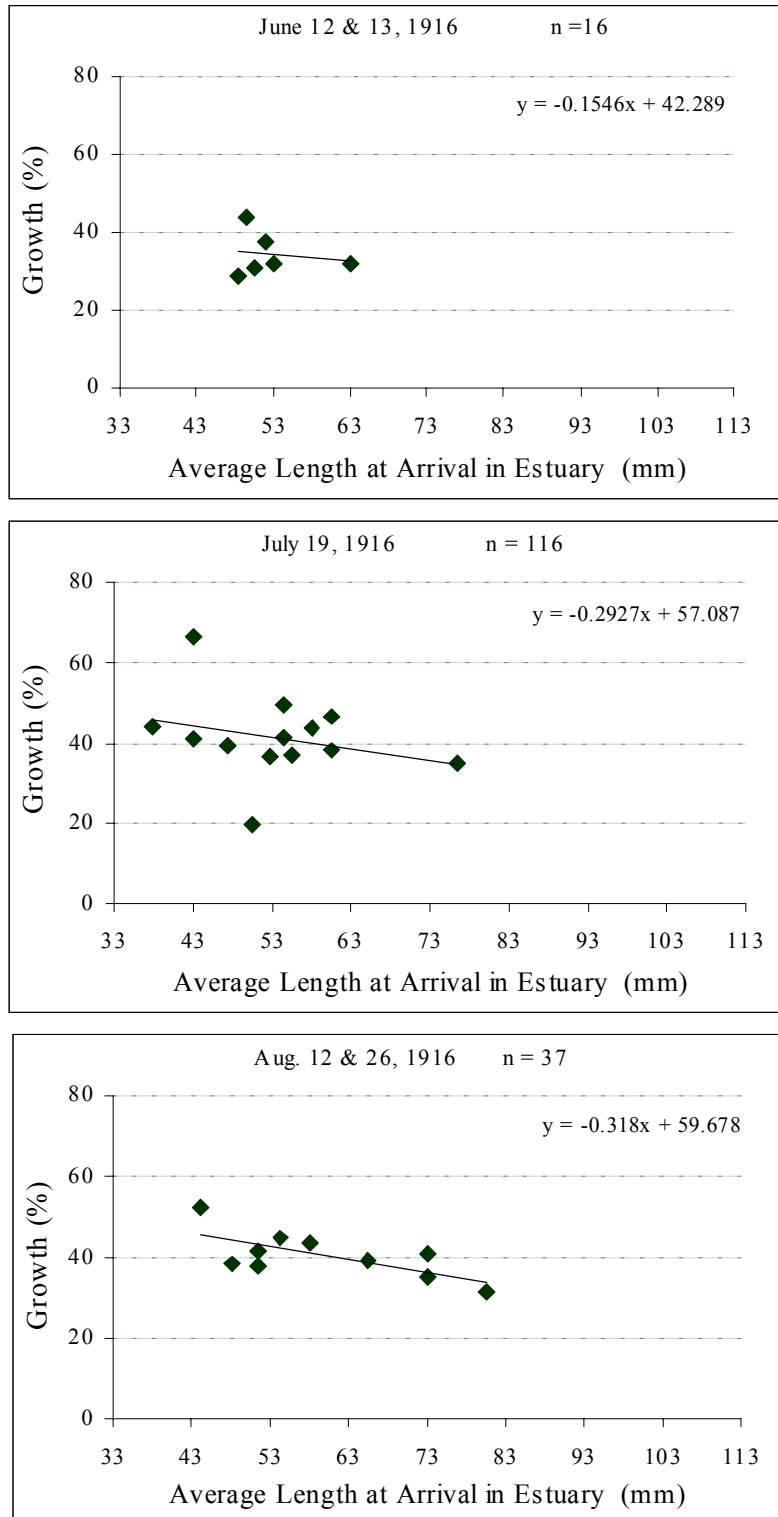
Figure 6.7. Trend lines between subyearling chinook salmon size at arrival in the estuary and percent of total length attributed to estuarine growth. All fish collected at Point Ellice in 1916 (Rich 1920).

Pelagic Habitat

Intertidal Habitat
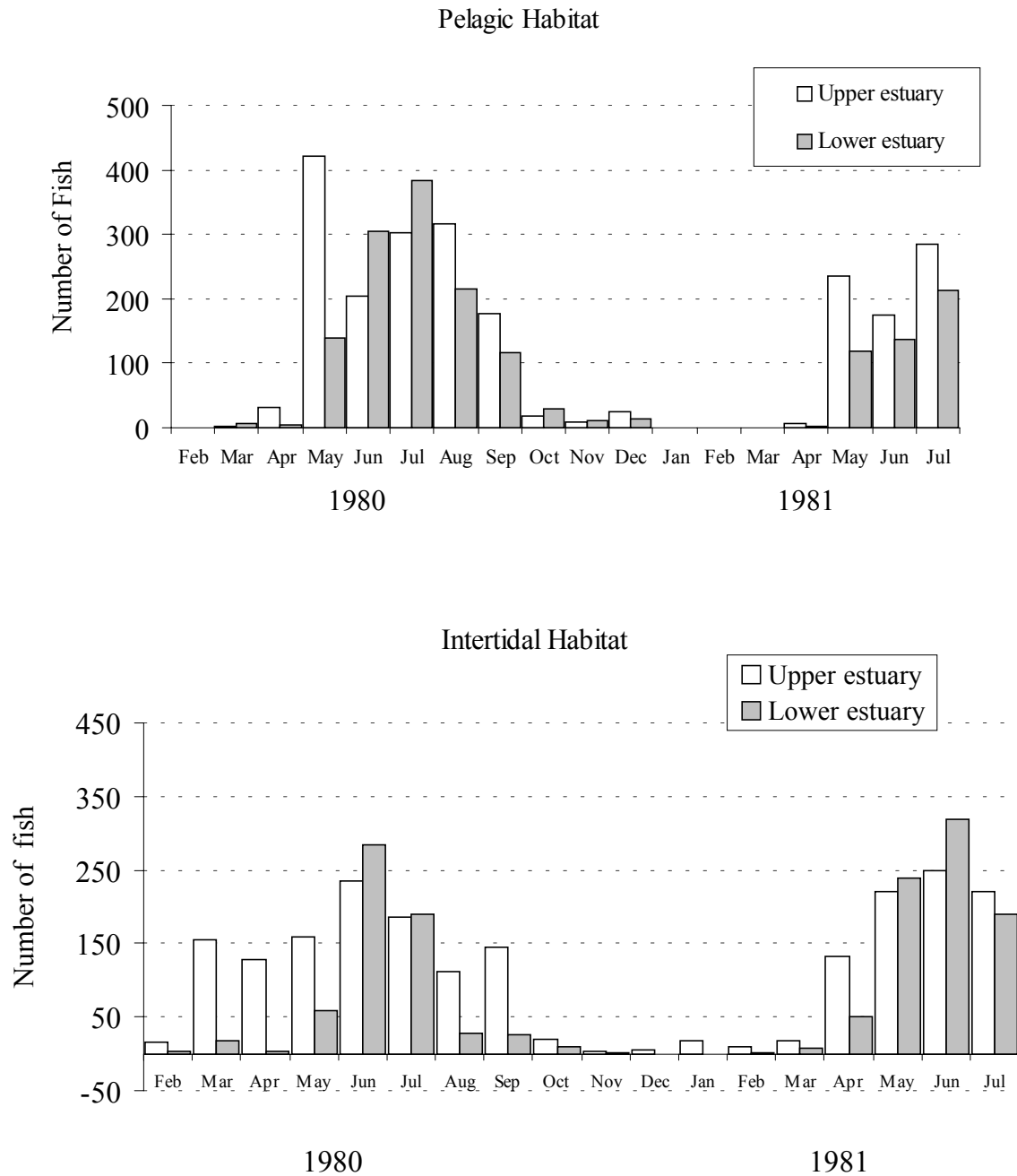
Figure 6.8. Subyearling chinook salmon recovery in the Columbia River estuary during CREDDP study (McCabe et al. 1986).
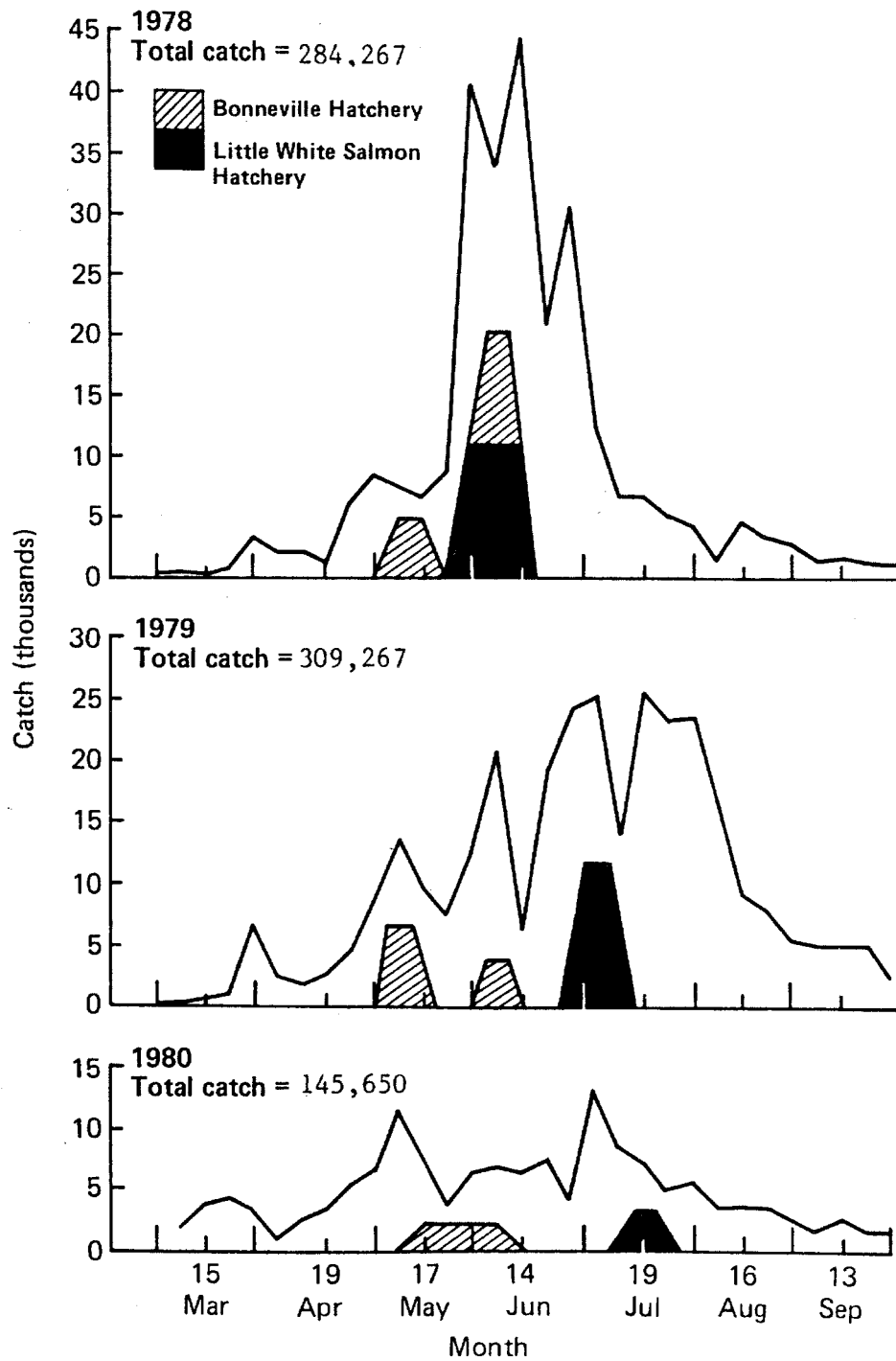
Figure 6.9. Timing correlation between peak abundance at Jones Beach and the arrival of hatchery-reared subyearling chinook salmon (reproduced from Dawley et al. 1985).

McIsaac (1990) determined that peak abundance for wild Lewis River juveniles reared in the hatchery were highly influenced by the date of hatchery release and did not necessarily track the timing of naturally reared fish (Fig. 6.10). Hatchery-reared chinook fingerlings were released between May and September during the 3-year study. The arrival times for the first subyearlings at Jones Beach were 3 to 5 days following the date of release from the hatchery, regardless of the time of year of the release. Conversely, Lewis River wild fish arrived at Jones Beach in early or mid-July during the study except for 1980 migrants, which arrived June 1 probably because of the eruption of Mount St. Helens. The Lewis River study determined that the wild Lewis River juveniles contributed to a higher rate of adult returns than the hatchery-reared stock (McIsaac 1990).

Habitat Use

Our present knowledge of estuarine habitat use in the Columbia River estuary by juvenile chinook salmon is extremely limited. The only study designed to differentiate habitat use was by the CREDDP, but it primarily surveyed sloping beaches off main channels ("demersal slopes"), peripheral bays, and open, pelagic habitats (e.g., McCabe et al. 1986). Because CREDDP infrequently surveyed small tidal channels, sloughs, or other shallow, off-channel habitats, fish abundance was associated with a limited number of habitat types.

Durkin (1982) reported high concentrations of subyearlings in bays and shallow intertidal areas, particularly in Cathlamet Bay in 1980. The majority of these subyearlings originated from Washington State hatcheries and may have sought refuge in these shallow areas following their translocation and premature release into the lower estuary after the eruption of Mount St. Helens in 1980 (Durkin 1982). Fish originating from Oregon streams were generally collected in the near-shore habitats on the Oregon side of the river (Durkin 1982). McCabe et al. (1986) extended the analysis of Durkin and determined that subyearlings were more abundant in intertidal than in pelagic habitats, although such comparisons were difficult because different gear types were used to sample each habitat type. Stomach analyses showed that the subyearlings were actively feeding in the estuary (Durkin 1982, McCabe et al. 1986). Dawley et al. (1986) and McCabe et al. (1986) found that the mean sizes of subyearlings increased in the deeper habitats and hypothesized that as subyearlings grew, they migrated farther off-shore.

Migration routes and habitat preferences of yearling chinook salmon have been well documented, particularly for hatchery fish. Both Rich (1920) and Dawley et al. (1986) observed that yearling migrants (wild and hatchery) found in the estuary before June were concentrated along the shoreline. These migrants comprised the highest catches of yearlings for Dawley et al. (1986). In a more recent 3-year study, hatchery-reared yearlings were radio-tagged and tracked through the estuary (Schreck et al. 1995, 1996, 1997; Schreck and Stahl 1998). These fish primarily used deep-water channels, side channels, and, in two seasons of observation, shallow-water areas (< 5-ft deep at high tide) of the estuary.

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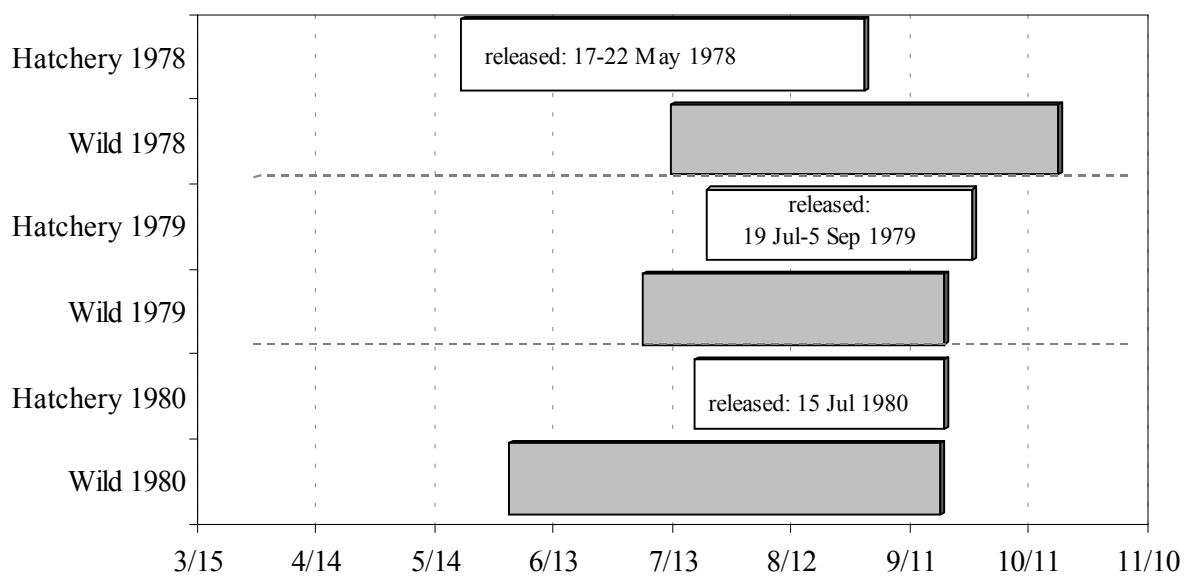
Figure 6.10. Recovery timing of wild and hatchery subyearling chinook salmon from the Lewis River at Jones Beach (McIsaac 1990).

Length Characteristics

Recent trends in the fork lengths of juvenile chinook salmon differed from those described by Rich (1920). Relative to Rich's results, contemporary surveys revealed a narrower range of chinook salmon sizes and a more homogeneous distribution of size classes (Fig. 6.11, Table 6.6). The modern collections lacked smaller subyearlings (< 60 mm FL) during early fall (Fig. 6.12). In addition, modern subyearling chinook salmon collections had a less dramatic increase in length and an earlier stabilization in mean size during the juvenile rearing period compared to the 1916 collections.

Contemporary size distributions of chinook salmon during the spring and summer rearing periods differ from those recorded during Rich's (1920) survey. In 1916, the mean fork length of subyearling chinook collected by beach seine was 46.8 mm in May and steadily increased through July. Mean fork length remained the same from July to August. In contrast, subyearling fish of unknown or hatchery origin collected at Megler, Washington, in 1966 and McGowan, Washington, in 1980 were substantially larger during the initial sampling period (mean FL > 70 mm). Mean size did not steadily increase during the spring and summer, and mean fork length increased sharply in the fall (Figs. 6.13-6.15b; Earl Dawley, NMFS Point Adams Field Station, 520 Heceta Place, Hammond, OR, 97121, Pers. commun., March 2000).

Estuarine Residence

Because there are no contemporary scale data available to reconstruct life-history characteristics and estuarine growth of chinook salmon, present-day estimates of estuarine residence times are based primarily on mark-recapture studies. Most of these studies were designed to estimate travel times down to the estuary and survival rates of selected groups of hatchery-reared fish rather than to assess estuarine residency. There are no representative samples of an estuarine-rearing chinook population. However, Dawley et al. (1986) marked six groups of hatchery-reared (Washougal Hatchery) fry, released them into the lower river, and recaptured them at Jones Beach (RKm75). They determined that these fry utilized the estuary for an extended period (approximately 3 months) and moved both above and below Jones Beach based on repeat captures of individuals. The average size of these fish was larger than the remaining hatchery-reared fish passing Jones Beach that apparently did not use the estuary (Dawley et al. 1986).

Dawley et al. (1986) estimated travel rates of marked subyearling chinook salmon released from hatcheries throughout the basin and recovered at Jones Beach (RKm 75) and in the river plume. They established a migration rate of 6 days or less from Jones Beach to the river mouth as determined by the recovery of fish from 16 uniquely marked groups of hatchery fish. The estimate was based on the date of the first arrival to pass Jones Beach and the date of the first arrival recovered at Clatsop Spit. This rapid movement through the estuary suggests only minimal periods of estuarine rearing for hatchery-reared subyearling chinook salmon. However, this method may not accurately depict estuarine residency.

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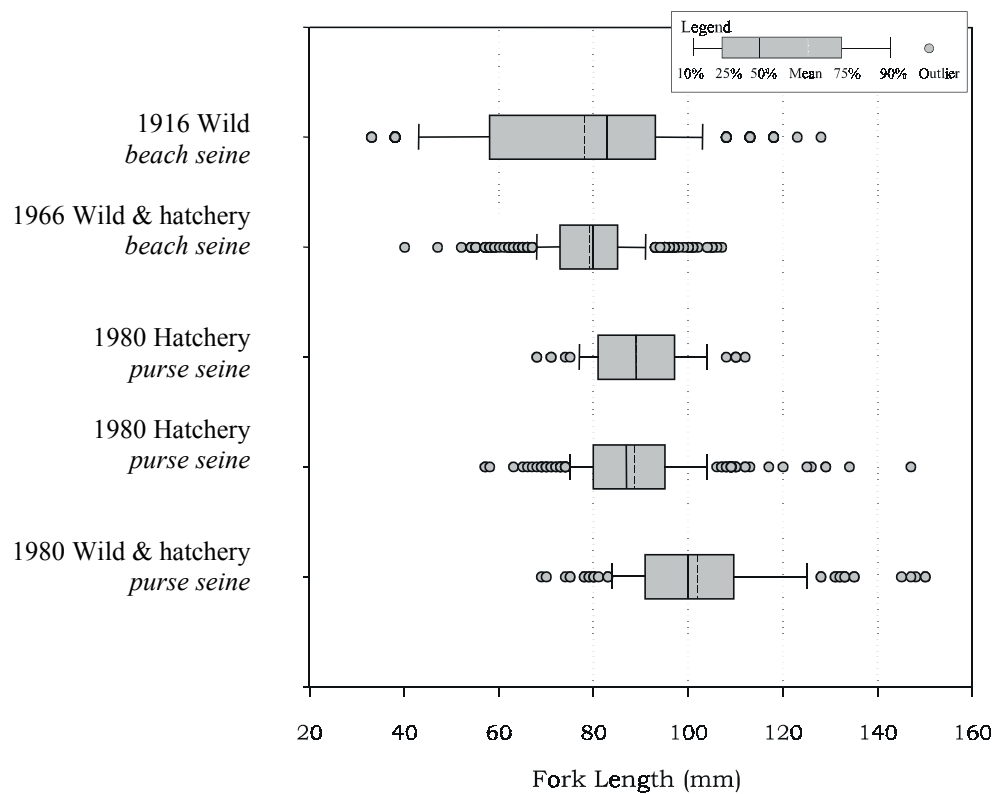
Figure 6.11. Fork length characteristics of subyearling chinook salmon collections from three studies in 1916, 1966, and 1980 in the lower Columbia River estuary (Rich 1920; Dawley et al. personal communication, 1985). Data presented in quartile distributions and all outliers are included.

Table 6.6. Fork length (FL) distribution (mm) of juvenile chinook salmon from various years of sampling in the middle Columbia River estuary (Rich 1920; Earl Dawley, Point Adams Biological Research Station, Hammond, OR, Pers. commun. March 1985).

	Fork Length Range (mm)		
	50%	80%	
1916	60-95	45-105	Wild
1966	73-85	68-91	Unknown origin
1980	80-95	75-105	Hatchery origin
1980	91-110	85-125	Unknown origin
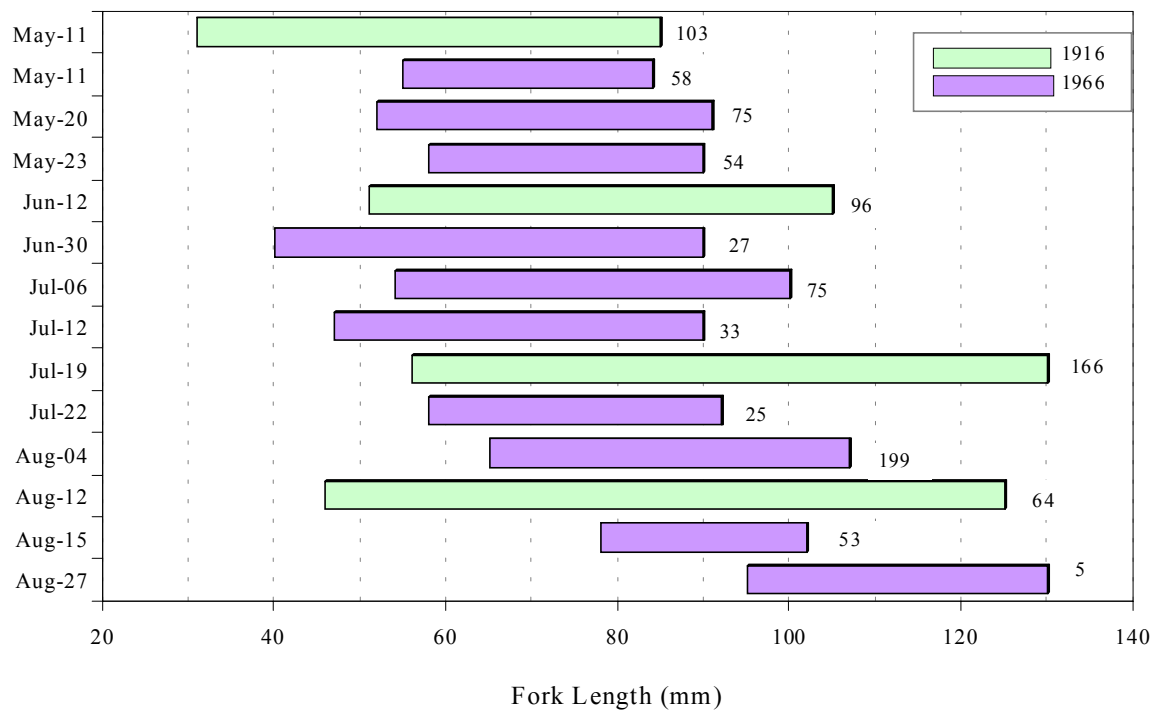
Figure 6.12. Fork length ranges of subyearling chinook salmon collected in 1916 at Point Ellice and in 1966 at Megler, Washington, in the lower Columbia River estuary (Rich 1920; Earl Dawley, Point Adams Biological Research Station, Pers. commun., March 1999).
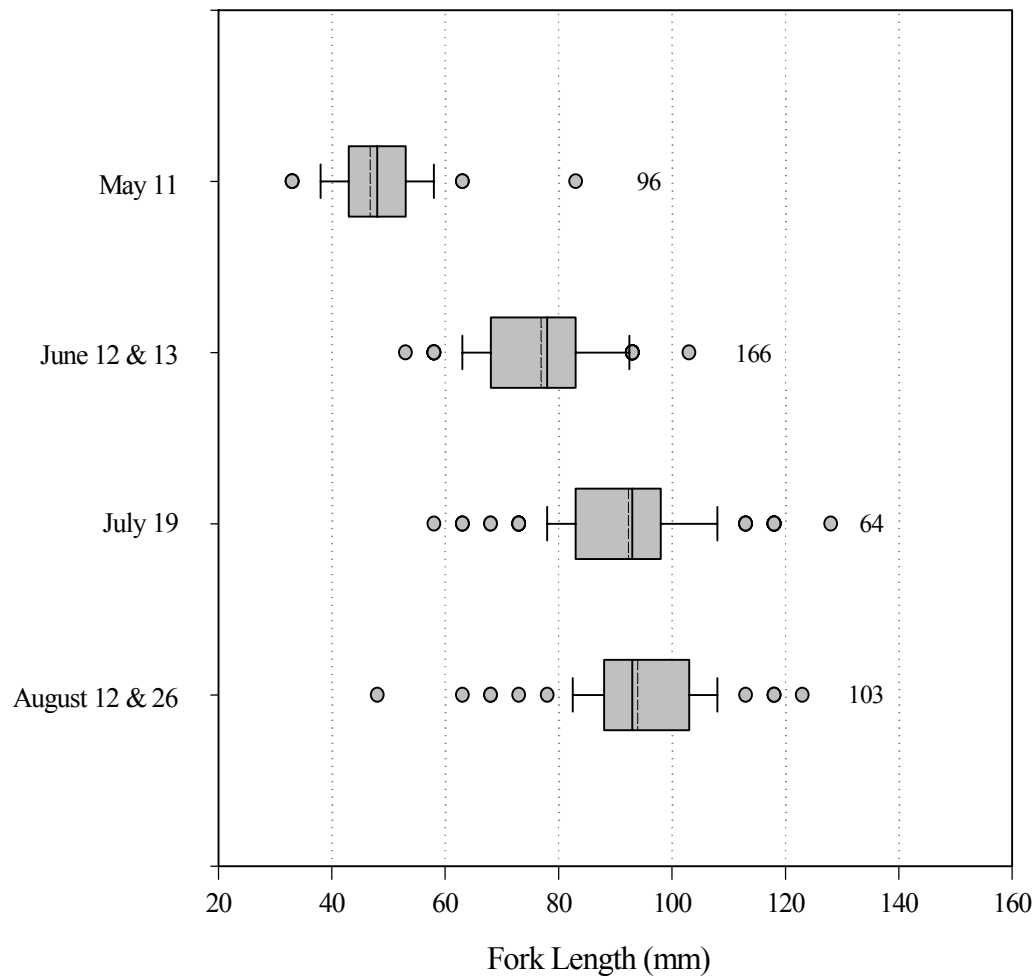
Figure 6.13. Fork length characteristics of subyearling chinook salmon recovery in the Columbia River estuary at Pt. Ellice in 1916 (Rich 1920). Data presented in quartile distributions with all outliers included.

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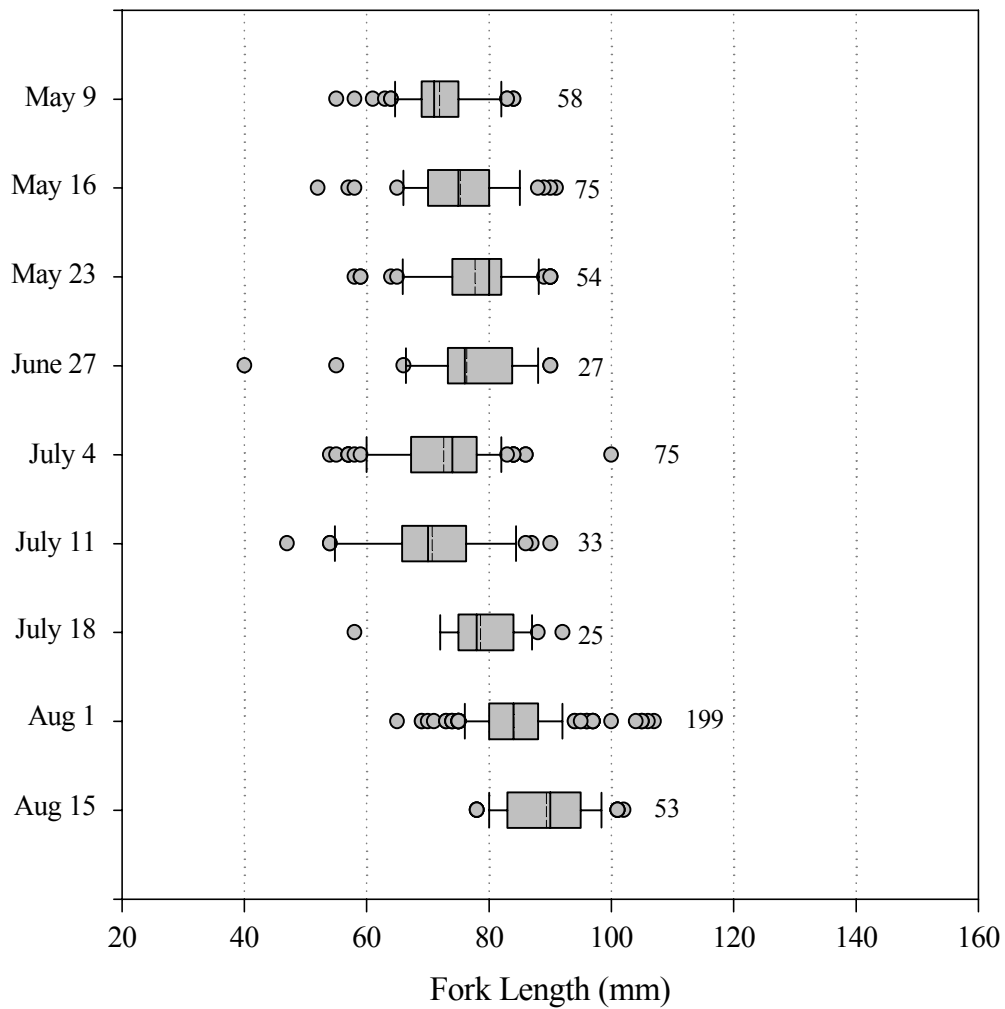
Figure 6.14. Fork length characteristics of subyearling chinook salmon of wild and
hatchery origin recovered in the Columbia River estuary at Megler,
Washington, in 1966 (Earl Dawley, NMFS, Pers. commun., May 1999).
Data presented in quartile distributions and all outliers are included.
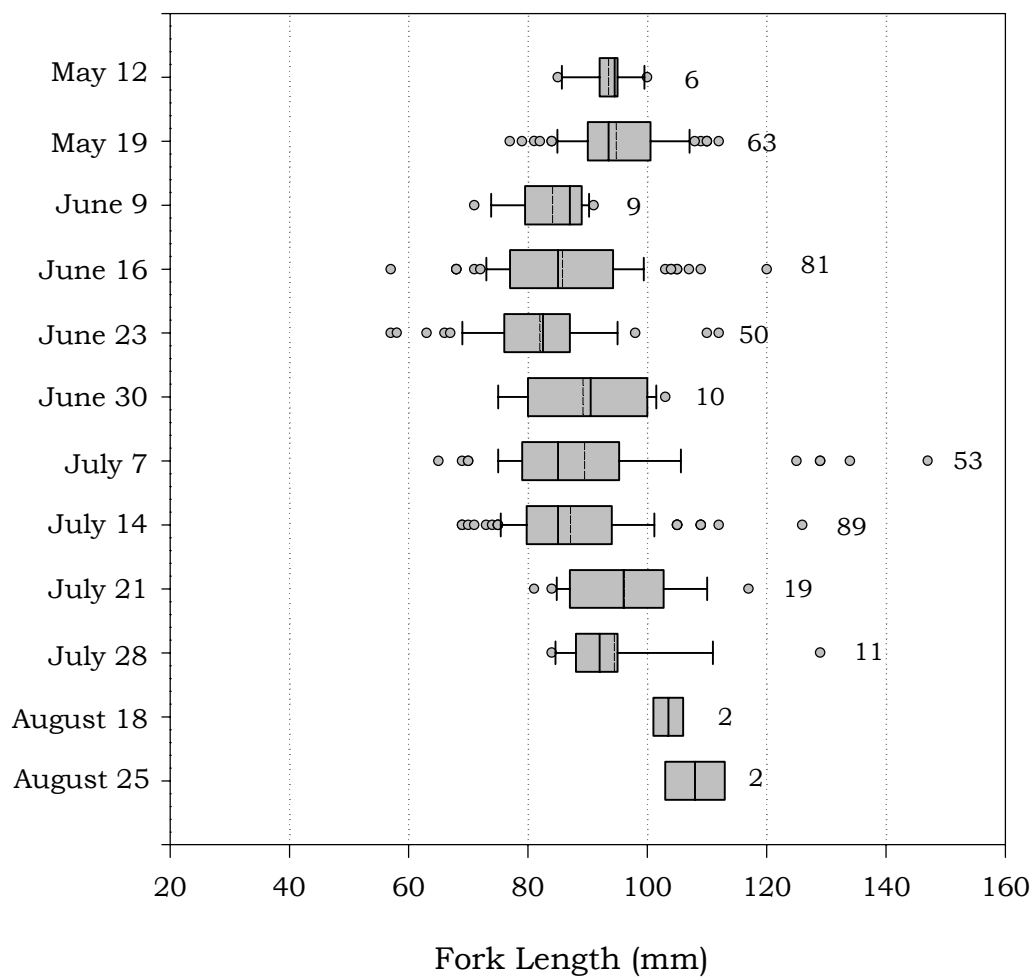
Figure 6.15a. Fork length characteristics of subyearling chinook salmon of hatchery origin recovered in the Columbia River estuary between RKm 16 and 20 in 1980 by Dawley et al. (Pers. commun., 1985). Data presented in quartile distributions and all outliers are included

SARE draft: Performance
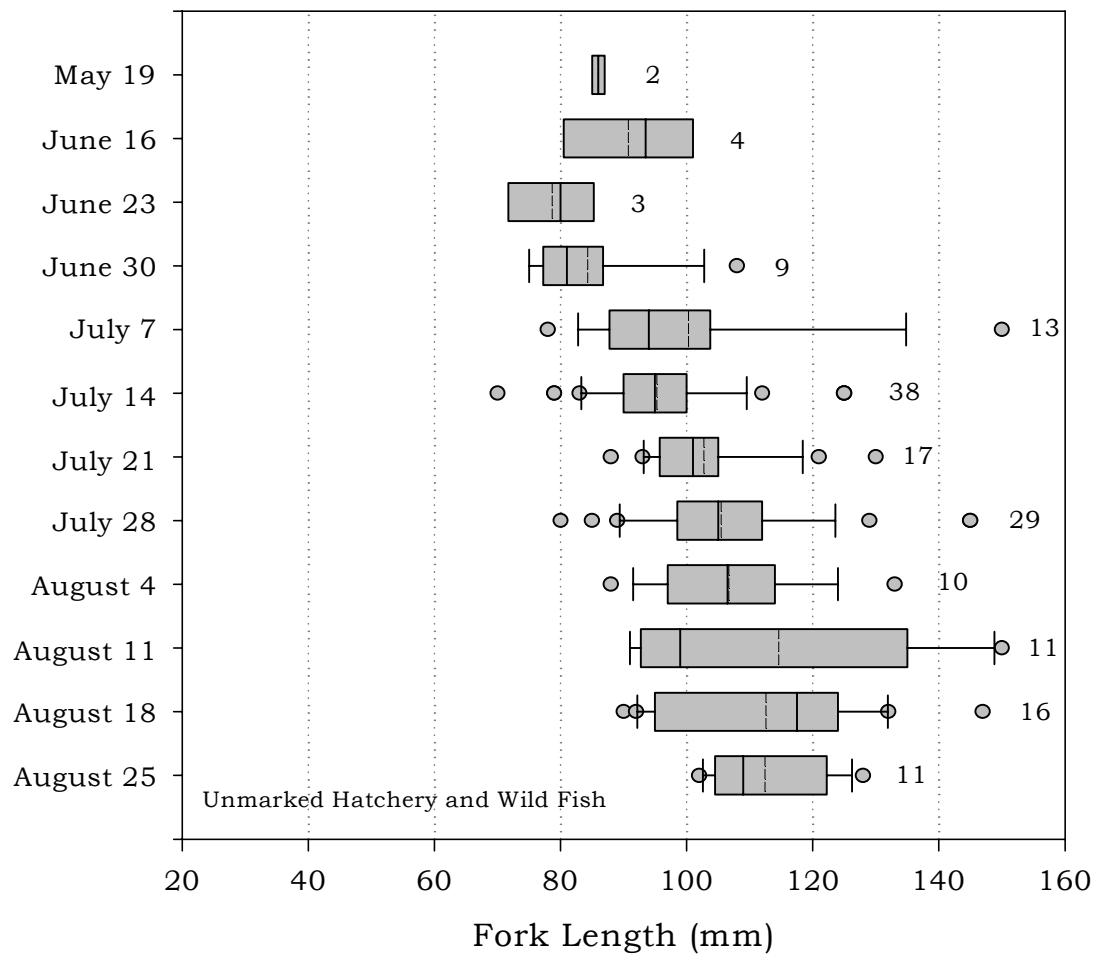
Figure 6.15b. Fork length characteristics of subyearling chinook salmon of unknown
origin recovered in the Columbia River estuary at RKm 16 (McGowan,
Washington) in 1980 by Dawley et al. (1985). Data presented in quartile
distributions and all outliers are included.

Discussion

Change in Estuarine Life Histories

Historically, chinook salmon in the Columbia River exhibited a diversity of life-history strategies, using a continuum of streams, rivers, the estuary, and potentially the plume as nursery areas at different times of their life cycle. Anthropogenic changes to the Columbia River ecosystem and the salmon populations have constrained and homogenized the present-day life histories. This interpretation is consistent with recent reconstructions of chinook salmon life histories upriver (Lichatowich and Mobrand 1995, ISG 2000) and by our comparison of past and present life histories in the estuary. Our assessment further supports the hypothesis that the simple ocean-type and stream-type dichotomy traditionally used to characterize chinook salmon life histories is an oversimplification of juvenile rearing behaviors.

The diversity of life-history strategies of chinook salmon is evident from the historical collections of Rich (1920). Several forms of ocean-type life histories were described based on fork length, time of collection, and the results of Rich's scale analyses. Variations in juvenile life history were apparent by differences in the timing and duration of rearing in natal stream, river, estuary, and ocean environments. Rich suggested that subyearlings that originated from the same tributary migrated as a group based on similarities in fork length and scale characteristics in each collection. Ocean-type juvenile salmon migrated to the estuary as fry or fingerlings. Fry continuously migrated to the estuary from early spring to early fall. Fingerlings arrived in the estuary throughout the year. Some remained for extended periods while others probably migrated rapidly seaward.

Rich's (1920) collections and scale analyses suggest as many as five variants of ocean-type life histories, including fry migrants and four types of subyearling migrants. Subyearlings devoid of scale checks reared in their natal stream and migrated directly to the estuary. Fish with this scale pattern were collected throughout the sampling period. Estuarine rearing subyearlings possessed an intermediate check and, depending on its position, arrived in the estuary as fry or fingerlings. Subyearlings with only a primary check, indicating an adfluvial life history, did not appear in estuary collections until late fall. Subyearlings with both primary and an additional outer check constituted 59% of all fish collected in the fall of 1914 and 1915. Depending on when in the fish's life history the additional outermost checkmark formed, it could be classified as an intermediate check or an annulus (Rich 1920).

Rich discussed in detail the ambiguity surrounding the interpretation of the annual and intermediate checks. Based on the fork-length ranges and approximate timing at which the outermost check mark may have occurred, we cannot rule out that a component of subyearling chinook with an adfluvial and an additional check mark had reared for a time in the estuary.

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The uniform sizes of subyearling chinook salmon in modern collections may reflect the influence of hatchery production on size characteristics or a reduced abundance in diversity of wild fish entering the estuary from upriver. This homogeneity of size characteristics is clear when comparing estuary collections from 1916 to 1966 and 1980 (Fig. 6.11). Differences in gear type (purse or beach seine) or year of sampling (1966 and 1980) do not explain apparent changes in juvenile size distribution in the estuary.

While deep-water gear (purse seine and trawl nets) may have been biased for larger fish, we believe the size structure of the subyearlings has been truncated and that these changes cannot be explained solely by gear selectivity. Dawley et al. (1986) determined that the purse seine satisfactorily sampled subyearlings as small as 60 mm FL. In addition, McCabe et al. (1986) stated that small subyearlings were collected in purse seines and large subyearlings were captured in beach seines early in the summer.

The opposite was true later in the summer when small subyearlings dominated the beach seine collections and large subyearlings were predominately collected in purse seines. These patterns suggest a shift in habitat use among juvenile salmon of various sizes, which may explain some of the differences in salmon size characteristics among gear types and habitats. Such differences do not exclude the possibility that small subyearlings ($\leq$ 60 mm) may be collected by either gear type.

Hatchery-released fish probably had little influence on the size distribution of chinook in Rich's (1920) samples. Although we cannot eliminate the possibility that Rich collected some hatchery fish, he was confident that all of the subyearlings sampled in the estuary were of wild origin. Hatchery practices in Oregon shifted in 1910 from releasing unfed fry to feeding fry in runway ponds and releasing juveniles as larger fingerlings. In 1916, hatcheries released approximately 95 million fry and fingerlings (Lichatowich et al. 1996). Bonneville Hatchery, the largest production facility at that time, released fingerling chinook salmon from April to September (Wallis 1964).

Therefore, the fry that Rich (1920) recovered in March were most likely wild fish. Rich contrasted scales of fry collected in the estuary in 31 March and 1-2 April with those from fry sampled at the Clackamas Hatchery on 11 April. While all hatchery fry had well-developed scales, many of the wild juveniles did not. Hatchery fry were somewhat larger than wild fry, 36 to 65 mm FL (n = 62) vs. 31 to 50 mm FL (n = 102), respectively.

The presence of large subyearlings may indicate the importance of the Columbia River estuary as a refuge for juveniles prior to ocean migration. In contrast, subyearlings in Canadian and Washington river systems enter the ocean at relatively small sizes (maximum 70 mm) and may use the sheltered marine transition areas of the Strait of Georgia and Puget Sound, respectively, as refugia before migrating to the open ocean (Healey 1980, Levy and Northcote 1982, Simenstad et al. 1982, Levings et al. 1991). Because no alternative marine transition areas are present outside the mouth of the

Columbia River, there may be advantages for many life-history types to rear for an extended period and grow to relatively large sizes before leaving the estuary.

Studies in other Oregon rivers suggest that subyearling chinook salmon may need to migrate at relatively large sizes (100 mm or greater) to have a high probability of surviving in the ocean. Limited data reported for a variety of coastal chinook salmon populations in Oregon show mean lengths at ocean entry ranging from 10 cm to about 16 cm (Nicholas and Hankin 1988). Within samples from various Oregon populations, estimated size at ocean entry rarely was less than 10 cm, although the mean sizes of fish entering each estuary was often much smaller. These results further support the concept that estuaries are important rearing grounds for subyearling migrants, particularly along the open Oregon coast, where no alternative marine transition areas are available to salmon during their seaward migration.

Although larger sizes at migration may often favor ocean survival, the persistence of smaller fry and subyearling life-history types among Oregon populations suggests that there is no single "threshold" size or time that chinook salmon must migrate to successfully return as adults (Nicholas and Hankin 1988). The wide diversity of historical times and sizes of migration through the Columbia River estuary may have evolved to accommodate a considerable range of oceanographic, estuarine, and riverine conditions. Rich's (1920) scale analyses indicate that juvenile chinook that reared in the estuary spent at least one week to a few months in the estuary.

To further support this, Rich (1928) examined adult scales and determined that Columbia River juvenile salmon migrated to the ocean as a continuum between ocean-type and stream-type life histories with the whole range of life histories contributing to returning adults. Ocean-type fry and stream-type juveniles were present but minor relative to other (subyearling) life histories. Diversity in residence times, migration times, and size at ocean entry suggests a strategy for maintaining flexibility within and among salmon populations in an unpredictable ocean (e.g., Spence 1995), even though larger sizes and/or later migration periods may be advantageous under some environmental conditions (e.g., Reimers 1973).

Estuarine residence times inferred from Rich (1920) concur with estimates for Fraser River, Nanaimo River, Sixes River, and the Rogue River but differ markedly from more recent estimates in the Columbia River. Many estuarine studies in the region report chinook rearing in estuaries for several weeks to two months (Healey 1980, Levings et al. 1986, Nicholas and Hankin 1988, Reimers 1973). In contrast, the only contemporary estimates of rearing periods for subyearlings in the Columbia River estuary were about a week for 16 groups of marked hatchery fish migrating past Jones Beach and recovered in the lower estuary (below RKm 18) (Dawley et al. 1986).

Because individual fish were not monitored and only a small number of fish from each marked group were recaptured in the lower estuary, we cannot be certain whether the estimated residence times are characteristic of most contemporary populations.

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Residence times were derived from the first fish from each tagged group captured at Jones Beach and at the estuary mouth and therefore, do not characterize the range of estuarine residence times. Dawley et al. (1986, p. 32) concluded that "the majority of fall chinook salmon fingerlings remain in the estuary for a relatively short period." If this is correct, then the residency of most hatchery fish has declined relative to the historical estimates reported by Rich (1920).

Our interpretations of past and present juvenile life histories for chinook salmon are clearly limited by the lack of basic biological surveys in the Columbia River estuary. The range of life-history types, estuarine-residence times, and growth estimates are based upon a comparison of three years of data (1916, 1966, and 1980) at a single site in the lower estuary. These data are not sufficiently comprehensive to depict the former or present diversity of salmon found among the full variety of habitats throughout the estuary or to describe variability in rearing behaviors over time. Without independent surveys or methods to validate Rich's (1920) results, scale analyses from 1914 to 1916 could be subject to unknown errors or misinterpretations. The inability to distinguish an annulus from an intermediate check prevents precise classification of some life-history types. But the affect of most past or present data limitations would seem to underestimate rather than overestimate the diversity of rearing behaviors in the basin.

The lack of research on subyearlings in shallow estuarine habitats, particularly tidal channels, sloughs, and marshes, may also limit understanding of life-history diversity as well as the rearing requirements of Columbia River chinook salmon. These shallow habitats, which are heavily used by subyearling salmon in other Northwest estuaries, may be particularly important off-channel refugia in a high-energy, river-dominated system like the Columbia (Healey 1982, Levy and Northcote 1982). Limited sampling has occurred in the lower Columbia River estuary (below RKm 75), while the upper estuary (above RKm 75) has not been studied. A variety of sloughs and side channels in the upper estuary offer potential refugia and rearing habitat for downstream migrants.

Modern methodologies used to monitor groups of salmon as they pass through the Columbia River estuary do not differentiate among various life-history types. Due to the difficulty of estuarine recovery of marked salmon, residency estimates have been based on a very small proportion ($< 6\%$) of the marked population (Dawley et al. 1986). Furthermore, such estimates are derived primarily from hatchery-reared fish, which constitute more than 95% of the marked population and are biased toward larger fish that can retain tags (Dawley et al. 1986). Contemporary estuarine peaks in salmon abundance have been associated with the timing of hatchery releases (Dawley et al. 1986). Hatchery influence on patterns of salmon abundance may help to explain the relative uniformity of juvenile size classes due to the release of large groups of similarly sized subyearling or yearling chinook. On the other hand, reported size distributions may underestimate present-day diversity in the estuary due to the limited sampling and recovery design, which targets groups of marked hatchery fish and ignores smaller subyearlings and the shallow-water habitats they may prefer.

While basic data on the life-history of wild chinook salmon was available in the early 1900s, the lack of scale collections and pertinent data in recent years prevent us from similarly classifying the juvenile life histories of contemporary salmon populations. We have found a limited scale archive for estuary samples of coho and yearling chinook salmon only, and these have yet to be interpreted. Interpretation of the coho salmon scales may be particularly useful given the multiple life histories of juvenile coho salmon recently described in the South Slough National Estuarine Research Reserve and in several other coastal estuaries (McMahon and Holtby 1992, Miller and Simenstad 1997, Miller and Sadro 2000).

The diversity of chinook salmon life histories we described from historical Columbia River data is consistent with the variety of life histories reported in other Northwest estuaries. The Rogue River and Sixes River estuaries, two small systems on the southern Oregon coast, had a similar or greater number of early life-history types than those documented in the Columbia River (Schlucter and Lichatowich 1976, Reimers 1973). Carl and Healey (1984) and Healey (1980) described at least three genetically distinct life-history types in addition to various times of migration for chinook salmon in the Nanaimo River Basin on Vancouver Island, British Columbia.

In Chapter 2 (Fig. 2.3), three generalized life-history strategies were proposed for chinook salmon in the Columbia River Basin. These strategies were distinguished by length of time spent in each freshwater environment, time spent in the estuary, and time and size at ocean entrance. From the analysis of Rich's (1920) data, this simple model was expanded to recognize six life-history types in the Columbia River, including five variants of subyearling life history (Fig. 6.16).

Based on Rich's results and the extent of freshwater habitat available before most Columbia River dams were constructed, it is hypothesized that one or more chinook life-history types historically used natal streams, mainstem rivers, or estuarine environments as alternative nursery habitats, with each brood of Columbia River salmon represented by a continuum of rearing and migrant behaviors spanning an 18-month period (Fig. 6.16). By contrast, it is inferred that ocean-type chinook salmon with estuarine rearing life histories are now substantially reduced in importance, leaving three principal life-history types in the basin: subyearling migrants that rear in natal streams and/or main rivers and a group of yearling migrants.

Historical and Contemporary Factors Affecting Salmonid Life Histories

The watershed, estuary, and salmon populations have undergone significant changes in the 80 years since Rich's (1920) study. However, many changes already had occurred prior to 1916: commercial harvest of salmon reduced spring chinook runs to remnant levels, timber harvest and related activities impacted watersheds and stream channels, large-scale mining was active in many watersheds, and sheep and cattle grazing were extensive (Lichatowich and Mobrand 1995, Lichatowich et al. 1996). Therefore,

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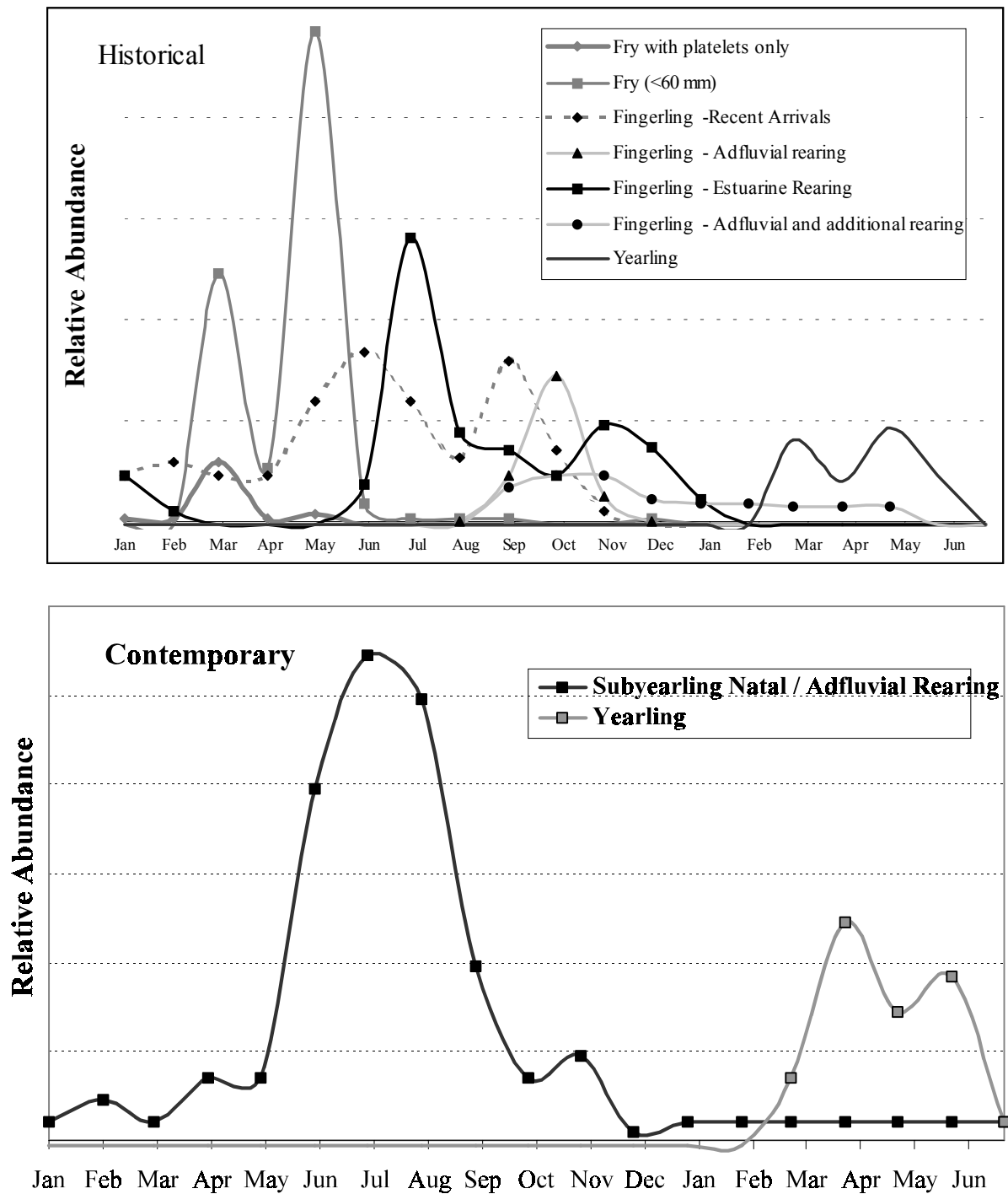
Figure 6.16. Historical and contemporary early life history types for one brood-year of chinook salmon in the Columbia River estuary. Historical timing and relative abundance based on historical sampling throughout the lower estuary (Rich 1920). Contemporary timing and relative abundance derived from Dawley et al. (1985) sampling at Jones Beach.

the results interpreted from Rich's study may not accurately reflect the full diversity of life histories that existed prior to European settlement in the region.

The apparent increased proportions of larger subyearlings with short estuarine residence times is consistent with the life-history response we might expect from the changes that have affected the Columbia Basin and salmon populations since Rich's survey. As proposed by the conceptual model (Chapter 2, Fig. 2.4) and supported by the assessment of estuarine conditions (Chapters 3-5), factors reducing diversity of estuarine rearing behaviors may include the quantity and quality of salmon habitat, both in the estuary and upriver; reduced genetic diversity through harvest pressures, population extinctions, and other causes; and the effects of hatchery rearing, release, and fish transportation practices on salmon size distributions and phenotypic behaviors. Although we cannot distinguish their individual contributions to life-history change or salmon decline, the following historical factors together may largely determine the present-day performance of chinook salmon in the estuary:

Salmon Harvest--Effects of commercial harvest on particular components of the total Columbia River production of chinook salmon were noted well before the start of the 20th century. Commercial harvest of adult salmon runs began in the early 1800s (Fig. 6.17) when salmon were so abundant that it was hard to imagine that there would not be enough for everyone (Hume 1893). Initially, commercial fishers targeted spring-run chinook adults, the superior canning variety (Lichatowich et al. 1996). Harvest pressure intensified in the 1860s.

As the number of the spring-run adults diminished, commercial fishers shifted to fall-run chinook in 1890. Concurrently, a significant reduction in the number of adults returning to spawn became apparent in 1890 in the Snake River Basin (Evermann 1895). A one-month delay in the spawning time of mainstem Snake River fall-run adults was also observed consistently for several years (Evermann 1895). Evermann noted that the adult runs passing over Lower Salmon Falls of the Snake River, which usually arrived in late July and early August, did not arrive until early September. On the other hand, Salmon River and Payette River adult runs completed the upriver migration at least one-month earlier than the Snake River run and in slightly higher numbers compared to other years. Fishing pressure was potentially affecting specific components of the chinook run in addition to the natural variability associated with populations.

The temporal and spatial differentiation of the adult runs increased the vulnerability of each sub-basin population to fishing pressure, which has further compounded their natural volatility. Rich (1928) commented repeatedly that fishery managers must regulate harvest of the entire adult run and not target discrete segments to minimize the impact on any single population. The shift in harvest from spring- to fall-run stocks in the late 1800s could have redirected the fisheries impact onto the mainstem Snake River adult run while allowing the Salmon River and Payette River adult runs to recover. By 1938, Rich (1943) reiterated his support of ecosystem-based

Columbia River Salmonids Timeline

Sustained fishery
(1880 - 1920)

Salmon
harvest
began

(1820)

Cannery
and
intensive
fisheries
begins
(1866)

Harvest
peak (1883)

Marked
Decline
(1911)

*

| 1800 | 1820 | 1840 | 1860 | 1880 | 1900 | 1920 | 1940 | 1960 | |

Fall
Chinook
harvest
begins
(1890)

75% of
harvest
(1912)

Fall
chinook
50% of
cannery
harvest
(1920)

95% of
canneries
(1892).

Spring and Summer
Chinook
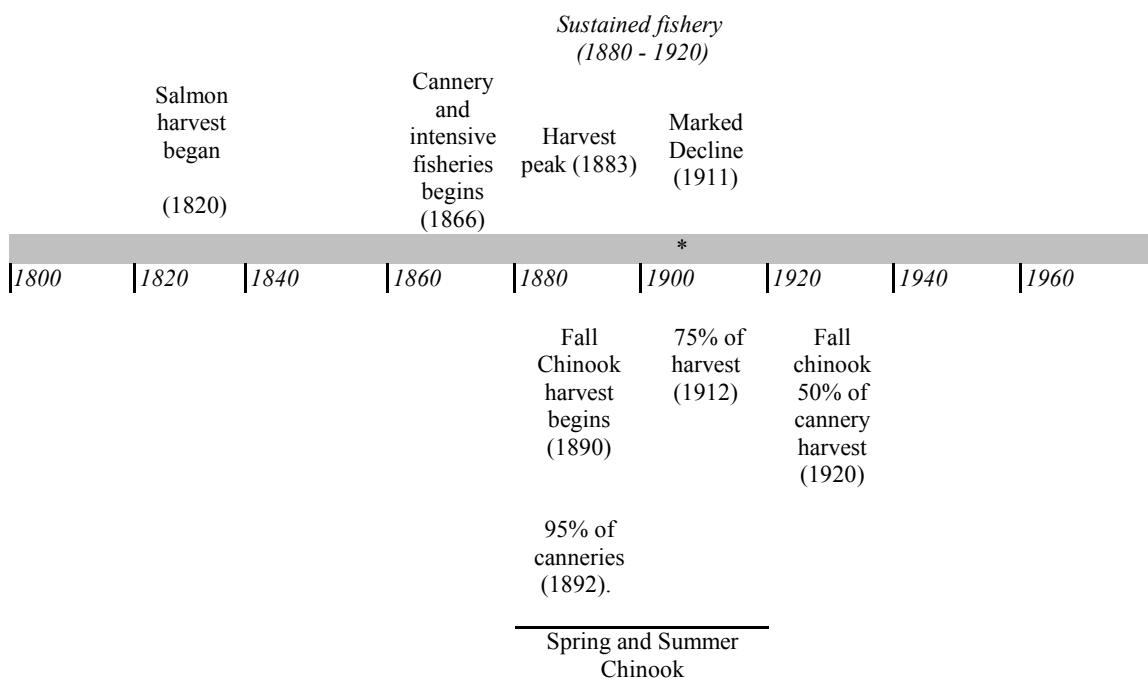
* Juvenile sampling by Rich 1914-1916

Figure 6.17. Harvest timeline for chinook salmon from 1800 to 1916 based on significant events presented by Oregon State Board of Fish Commissioners (1890, 1892), Hume (1893), Craig and Hacker (1940), Fulton (1970), Beiningen (1976), Smith and Wahle (1979), and Lichatowich and Mobrand (1995).

harvest regulations after completing fish counts and noting the greater abundance of fall-run adults, which had recently received protection by the closure of the lower river fall-run fishery starting on 25 August of that year. The effects of the harvest pressure were obvious from the fish counts going over Bonneville Dam, since harvest was shifted back to spring-run chinook salmon, and their abundance fell accordingly.

One affect of harvest and other intensive selection pressures in the Columbia Basin may have been the development of a lesser number of relatively discrete salmon runs. Historically, chinook salmon in the Columbia may have been composed of a broad continuum of spawning populations distributed across the entire habitat spectrum (Miller and Brannon 1981, Beaty 1992). Multiple changes over the last century, including the effects of intensive fisheries, may have selectively eliminated components of this continuum while promoting others.

For example, Thompson (1951) suggested that the upriver bright stock, a distinct group of fall chinook that spawns in late August to September, may have developed from the late tail of the summer run, which was protected by a long-term fishery closure. Rapid growth of Columbia River brights may have been aided by additional habitat opportunities created by heavy exploitation on other stocks (Beaty 1992). Today, a majority of the fall chinook run still passes Bonneville Dam during late summer (Fig. 6.18).

Because the early life-history strategies of chinook salmon are directly linked to the seasonal timing of the adult runs, changes in spawning populations during the last 80 years may have directly affected patterns of estuarine rearing. Rich (1943) analyzed scales from returning adults in the Columbia River and determined that the majority of the spring-run adults had stream-type life histories and the fall-run adults were dominated by ocean-type life histories, but both types were present from May to September (Fig. 6.19). Summer-run adults exhibited both life-history types depending upon where in the basin the juveniles originated.

Snake River Basin summer-run adults are typically stream-type migrants, while mid-Columbia River summer-run adults (i.e. Hanford Reach spawners) are ocean-type juveniles. Fisheries that inadvertently targeted specific populations of returning adults reduced the production of the juvenile life histories associated with those populations. By decreasing the abundance of wild populations and replacing a broad continuum of spawning populations with a few discrete stocks, harvest and other selective pressures have diminished life-history diversity in the Columbia River Basin, including some subyearling life-history types that may have used the estuary.

Habitat Loss--Habitat degradation and its adverse effects on salmon were noted as early as 1894 when mining in the Snake River watershed destroyed chinook spawning beds and contributed to the collapse of a popular Native American fishing site (Evermann 1895). Habitat loss and degradation has been and continues to be a major influence on the abundance and diversity of salmon in the Columbia River (Nehlsen 1995, Lichatowich et al. 1996). Chinook salmon populations from the upper Columbia River
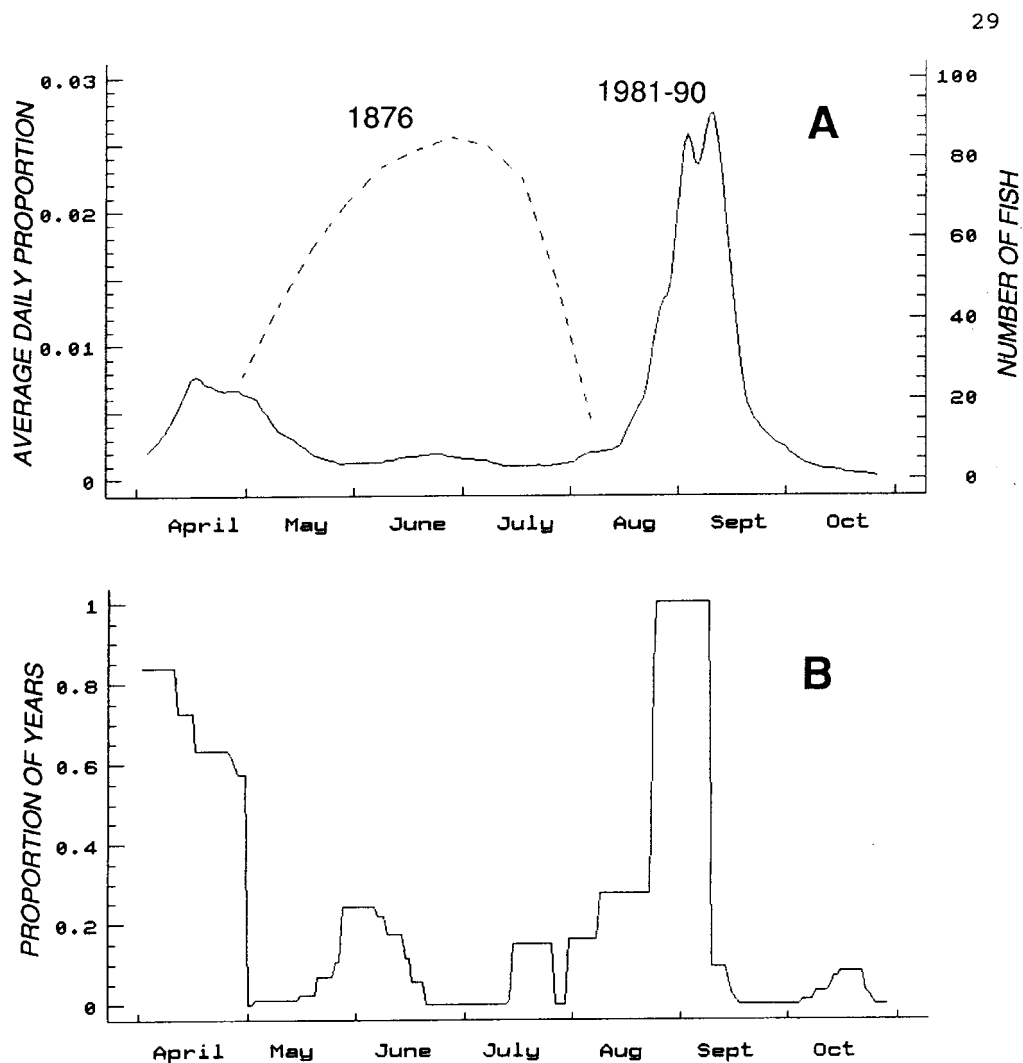
Figure 6.18. Seasonal protection of salmon runs (B) and the effect on historical and
contemporary adult run timing (A) in the Columbia River (reproduced from
Beaty 1992).
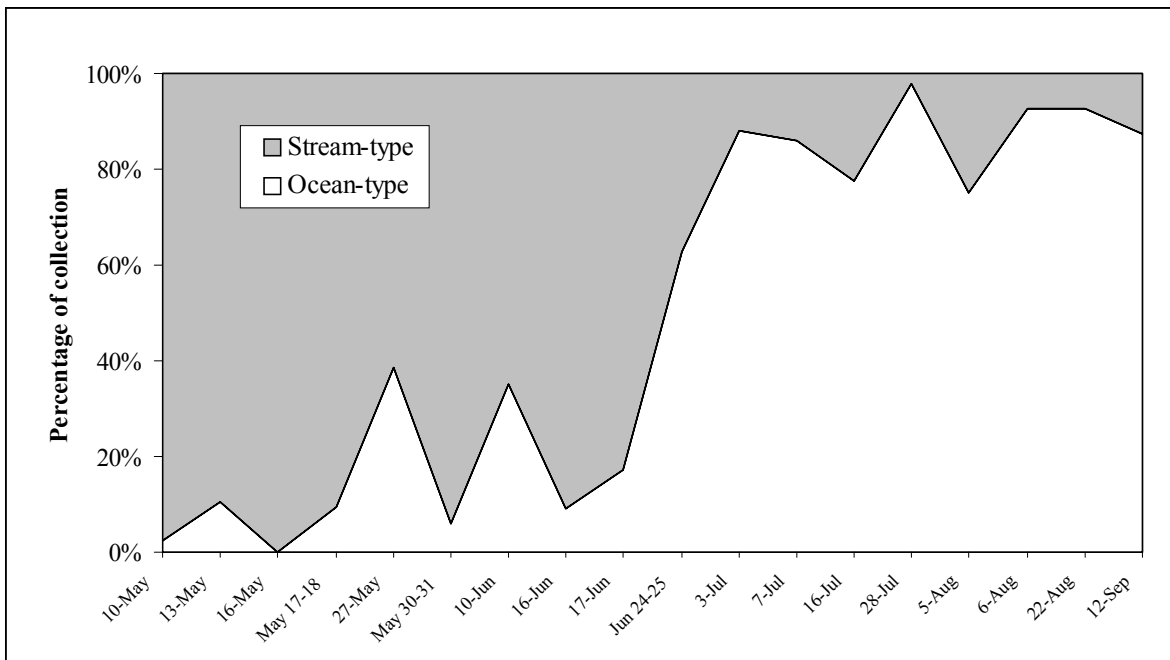
Figure 6.19. Interpretation of early life-history behavior based on scale patterns from returning salmon adults collected in the Columbia River estuary, 10 May–12 September 1919 (Rich 1925). Sample dates are not equal time intervals.

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Basin in British Columbia and Alberta, middle Snake River Basin and above, and the greater part of the Deschutes River Basin have been extinct for at least 40 years due to impassable dams (Chapter 1, Fig. 1.1).

The effects of blocking upstream passage were two-fold, reducing basin-wide productivity and salmon diversity. In the Snake River, ocean-type chinook salmon now occupy only 17% of the historical habitat (Hassemer et al. 1997). The Deschutes River Basin, now inaccessible above RKm 160.9, encompassed a highly connected cold water tributary system (Metolius River), an extremely large warm water tributary system (Crooked River), and a mainstem system. It may have been one of the greatest contributors to chinook salmon production in the Columbia River and probably included a wide variety of life-history types associated with the diverse freshwater habitats (Burke et al. in press).

Loss and degradation of habitat throughout the Columbia River Basin has reduced its productive potential and concentrated the remaining salmon into more limited and highly fragmented regions. Dam construction together with temperature increases in the mainstem and lower sub-basins have diminished habitat opportunity upriver and substantially reduced the proportion of ocean-type migrants that are now produced in the Columbia (ISG 2000).

Loss of subyearling migrant types from summer and spring spawners has likely occurred in many upriver areas that historically offered optimal growth opportunity, particularly in the warmer middle portions of Columbia sub-basins (Lichatowich and Mobrand 1995, ISG 2000). Because subyearling migrants typically reside in the estuary for longer periods and use different habitats than those with yearling life histories, such losses could have an important influence on contemporary patterns of estuarine rearing by chinook salmon and could leave vacant various shallow-water estuarine habitats favored by smaller ocean-type juveniles.

On the other hand, habitat changes within the estuary (see Chapters 4 and 5) could also account for the loss of some subyearling life-history types. Tidal marshes and swamps within the Columbia River estuary have been reduced by 65% (Thomas 1983). While these habitats have not been directly studied in the Columbia River, they are very productive rearing areas for small chinook and chum fry in other Northwest estuaries (Healey 1982, Levy and Northcote1982).

Additional wetland losses have not been quantified in the tidal freshwater region between RKm 75 and Bonneville Dam. However, losses of tidal riparian and floodplain habitats in this region from diking, filling, and railroad construction also appear to be significant. Other types of shallow habitat may have increased in the estuary (see Chapter 4), including an estimated 7% increase in the amount of shallows and flats, primarily due to the artificial creation of islands from disposal of dredged material (Chapter 5).

Yet these habitats do not provide the same functions as the marginal wetlands that have been removed, nor do they mitigate for the estimated 15% reduction in the estuary's historical tidal prism (Sherwood et al. 1990). Regardless of other shallow-habitat gains, considerable diking of wetland and floodplain habitats may have reduced the capacity of the estuary to support ocean-type subyearling salmon and may contribute to the apparent under-representation of these life histories in recent studies relative to the period of Rich's (1920) survey.

Flow Regime--Diking and flow regulation have drastically altered the available habitat and flow regime encountered by salmon in the Columbia River and the estuary. Diking of islands and margins of the estuary has eliminated refugia from high flows once available to juvenile salmon. At the same time, flow regulation has reduced spring freshet levels, and dams have created impoundments that alter the migratory habitat for juveniles traveling downstream. Prior to flow regulation, discharge levels were greater and the variability within short time-periods was higher (Sherwood et al. 1990).

Floodwaters of the Columbia River historically inundated the margins and floodplains along the estuary, permitting juvenile salmon access to a wide expanse of low-velocity marshland and tidal channel habitats. In addition, the greater seasonal variability of estuarine velocities and depths prior to flow regulation may have allowed a greater diversity of estuarine rearing behaviors by juvenile salmon. Reduced habitat potential coupled with an altered flow regime has probably reduced the productive capacity of the estuary for juvenile salmon.

The salmon data analyzed in this study encompass periods of a relatively free flowing river in 1916, a highly regulated river in 1966 and later, and the added effects of a volcanic eruption in 1980. Long-term river discharge values are available at The Dalles gauge for the period from 1878 to the present. The significant flow years are presented in Figure 6.20. The Dalles gauge measures flow throughout the Columbia River Basin except for the additional discharge from several lower river tributaries, most notably the Willamette River. The May 1980 eruption of Mount St. Helens, which added a huge quantity of silt and logs to the lower Columbia River estuary, hampered collection efforts until June (Dawley et al. 1986).

Excluding Mount St. Helens eruption, the sampling seasons of 1966 and 1980 were relatively benign under flow regulation, while the 1916 sampling season had one of the latest spring freshets on record, with flows on July 5 exceeding 20,000 m^3/s at The Dalles (USGS 2000). Although Rich (1920) made no mention of the river conditions, flows would have been between 15,000 and 25,000 m^3/s during Rich's sampling when the Willamette River contribution is taken into consideration (Fig. 6.21). Conversely, flows in 1966 and 1980 were probably close to 15,000 m^3/s including the Willamette River's contribution.
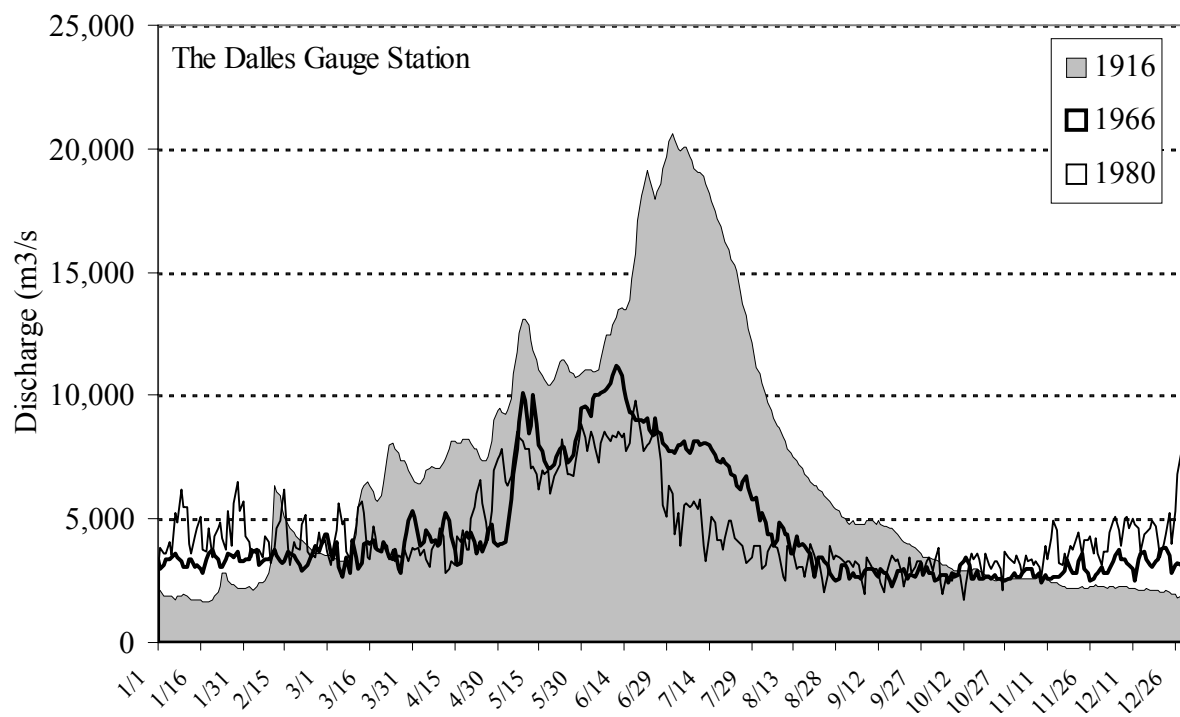
Figure 6.20. River discharges for 1916, 1966, and 1980 measured at The Dalles, Oregon, USGS gauge station (USGS 2000).
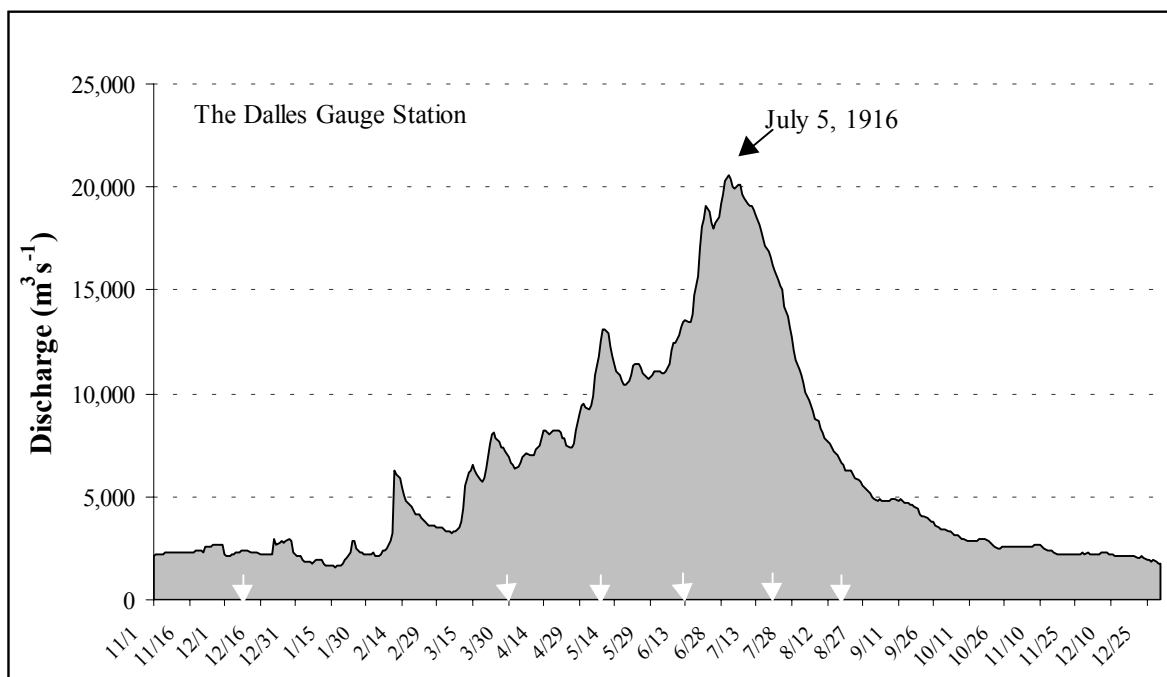
Figure 6.21 River discharge measured at The Dalles, Oregon USGS gauge station in 1916 (USGS 2000). White arrows represent sampling dates in the lower estuary (Rich 1920).

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The importance of shallow-water habitat for refugia is epitomized by the collection of juveniles less than 70 mm in the estuary during and after the peak freshet in 1916 (Rich 1920). The mid-July sample of 1916 included subyearlings that had resided in the estuary for at least 8 to 57 days, which encompassed the peak flow period. Prior to major physical alterations, the marginal areas of the estuary would have extended outward, expanding the surface area of the estuary dramatically and increasing the area of shallow, low-velocity habitat accessible to smaller juvenile salmon. It seems very likely that, to maintain their position within the estuary during 1916 peak flows, the smaller subyearlings must have sought refuge in shallow peripheral marshes and other off-channel habitats that would have been flooded.

Artificial Propagation of Salmon--The capacity of the estuary to support juvenile salmon may be influenced by the timing of hatchery releases and the abundance of hatchery juveniles in the Columbia River estuary. Several studies suggest that wild chinook salmon may have a much broader migration period to the estuary than that of hatchery fish. For example, Reimers and Loeffel (1967) beach seined seven tributaries in the lower Columbia River sub-basin until subyearlings were no longer captured. Their results showed considerable variability in the duration and completion of outmigration from each tributary into the estuary (Fig. 6.22).

For instance, the Klaskanine River population concluded their outmigration within one month and ended by the middle of June. The North Fork Lewis River population entered the estuary over a four-month period and did not complete their outmigration until the middle of October (Fig. 6.23). These results are consistent with McIsaac's (1990) 1977 to 1979 study of the North Fork Lewis River, which similarly documented considerable variability in wild fish migration timing to Jones Beach between sample years. The prolonged period of fry emergence and variable timing of outmigration in the North Fork Lewis River population indicates a variety of life histories among wild fish.

On the other hand, several studies have found that hatchery-reared chinook salmon migrate within a relatively narrow period. For example, Dawley et al. (1985) correlated the estuarine abundance and time of entry of subyearling chinook sampled at Jones Beach with their time of release from the hatchery (Fig. 6.9). Using PIT tags to monitor downstream movement through Lower Granite Dam, Achord et al. (1996) found that wild spring chinook migrated later, wild summer chinook migrated earlier, and both types migrated over a more protracted period compared to their hatchery-reared counterparts. The combined effect of hatchery-reared juveniles arriving in the estuary within an abbreviated and artificial migration window and at elevated numbers increases the density of juveniles and may artificially limit the productive capacity of the estuary.

Conclusions

Our evaluation of past and present salmon size distributions and migrations are consistent with the hypothesis that life-history diversity in the estuary has declined. Despite the obvious limitations of the available estuarine data, the results of several surveys from a similar estuary location provide a valid comparison before and after intensive development modified the Columbia River Basin. These results reflect the kinds of changes that might be expected based on the conceptual model (Chapter 2) and the results of upriver assessments that also document reduced life-history diversity in the basin (Lichatowich and Mobrand 1995, ISG 2000). The results suggest a more uniform size distribution among subyearling estuarine migrants; relatively constricted migration periods dictated by the timing of hatchery releases; and evidence of apparently shorter estuarine residence times compared with the early results of Rich (1920).

The physical conditions of the watershed and the salmon populations when Rich (1920) studied estuarine use and residency were already modified by development and intensive fisheries. Therefore, it is expected that greater diversity existed prior to his survey. Estuarine habitat for salmon has further declined in the 85 years since Rich sampled. We have also experienced a marked decline in wild populations, including the extinction of complete salmon runs, such that artificially propagated fish dominate present-day monitoring efforts and population strength indicators. It is very difficult to establish the importance and duration of estuarine residency by wild juvenile salmon under present conditions of reduced estuarine habitat and the predominance of hatchery-reared salmon.

Multiple factors may account for the apparent reduction of small ocean-type migrants in the estuary, including loss of both upriver and estuarine habitats that historically supported ocean-type life histories, flow modifications that have dampened established disturbance regimes and altered estuarine habitats, and genetic selection associated with intensive fisheries. Such changes are further amplified by hatchery programs that concentrate the time of salmon entry into the estuary and further accentuate larger subyearling and yearling life histories. By releasing large batches of similarly sized fish over restricted time windows, hatcheries may limit the timing of estuarine migrations, narrow the range of habitats selected by juveniles, and artificially elevate fish densities within the estuary. Thus, decreased diversity of rearing and migration behaviors may promote density-dependent interactions while preventing salmon from fully realizing the productive potential of diverse estuarine habitats.

SARE draft: Performance
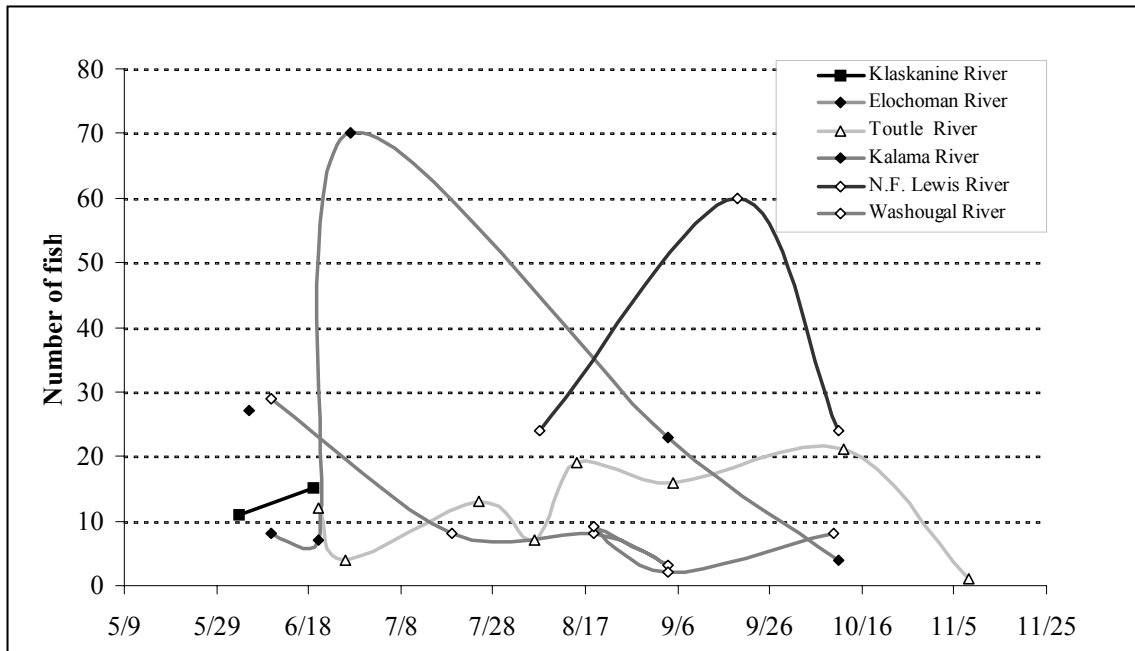
Figure 6.22. Time and relative duration of subyearling chinook outmigration from six tributaries into the Columbia River estuary during 1963 (Reimers and Loeffel 1967). Two sites were sampled in the Washougal River in August and September.

Wild Lewis River Recovery at Jones Beach 1980
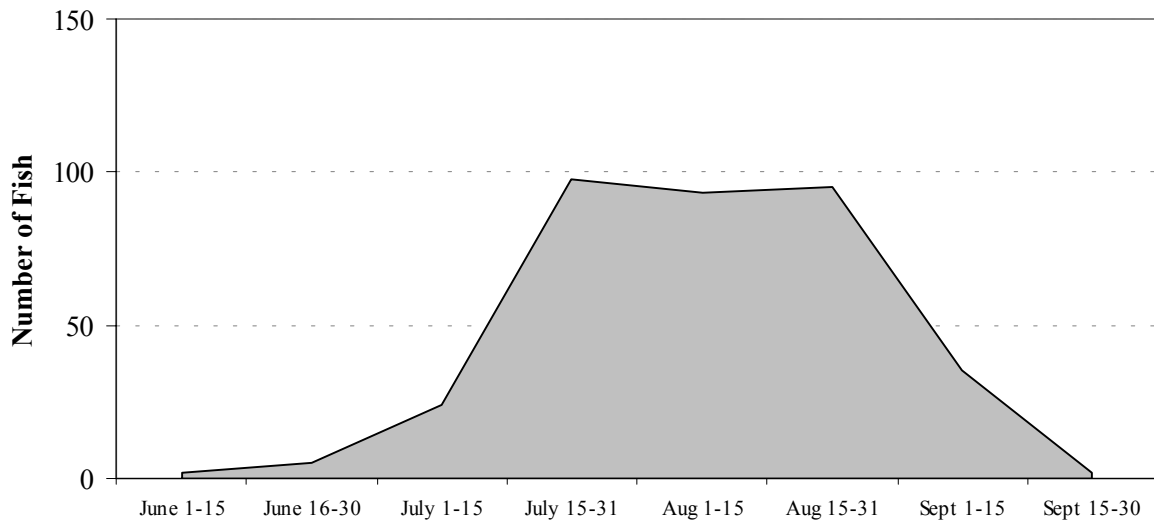
Figure 6.23. Duration of migration past Jones Beach of wild subyearling chinook salmon from the Lewis River in 1980 (McIsaac 1990).

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APPENDIX

Timeline for the Columbia River Basin: 1775 to 2000

Appendix Table 1. Time line of historical, scientific, legal, and natural events affecting salmonids in the Columbia River Basin.

Year	Historic/Scientific	Hydropower, Irrigation, and Navigation	Salmon	Peak Flow Events
1775	Bruno de Heceta, with the *Sonora*, sights the Columbia River, naming it the Rio San Rogue		Estimated historic Columbia River salmon runs fluctuated between 11 and 16 x 10^6 fish, of which native Americans may have captured 4.5 to 6.3 x 10^6	
1788	John Meares, aboard the *Felice*, encounters breakers across Columbia's entrance			
1790	Treaty between Spain and Britain grants territory to Britain			
1792	*Columbia Rediviva* under Captain Robert Gray, an American, enters estuary and names river; Broughton maps the estuary to Pt. Vancouver			
1793	Heceta maps the estuary			
1800	Major ashfall from Mt. St. Helens			
1804	Lewis and Clark expedition departs St. Louis			
1805	Lewis and Clark arrive at estuary			
1806	Lewis and Clark overwinter at Fort Clatsop and return east			
1807	David Thompson starts mapping upper Columbia River			
1810	John Jacob Astor's Pacific Fur Company, first permanent fur-trading colony, formed			
1811	Astor's Tonquin arrives; Fort Astoria constructed			
1813	Astoria sold to the North West Fur Co.			

Year	Historic/Scientific	Hydropower, Irrigation, and Navigation	Salmon	Peak Flow Events
1818			Salmon harvest begins of exclusively spring chinook	
1823			Astor Company exports pickled salmon to London	
1825	Hudson's Bay Company establishes Forts Vancouver and Coleville; disease reduces Lower Chinook Indian population to half of its historical level			
1827	First sawmill in Pacific Northwest built by Dr. John McLoughlin of Hudson's Bay Co. at site of Vancouver, Washington.			
1829	Capt. John Dennis brings the brig *Owyhee* into the Columbia River to pick up a cargo of salmon, only to spend two summers in the area; departs with 50 barrels of salted salmon, which he sold in Boston for $0.10 per pound			
1831	Mt. St. Helens ashfall			Two barrels of salmon put up by Captain John Dominis of the *Woyhee* sells for $0.10/lb in Boston
1833	First school in the Pacific Northwest established at Fort Vancouver, with John Ball as first teacher			
1836	The *Beaver*, first steamship on river, arrives at Fort Vancouver			
1837	M.C. Ewing, in USS *W.A. Talcum*, maps 90 miles upriver			
1839	Sir Edward Beecher conducts first official survey of bar conditions in HMS *Sulphur*			
1840	Approximately 800 Euro-American settlers in Oregon country			
1841	Com. Charles Wilkes surveys estuary for the United States; USS *Peacock* wrecks on north (Peacocks) spit			

Year	Historic/Scientific	Hydropower, Irrigation, and Navigation	Salmon	Peak Flow Events
1842	First frame house in area built by W. W. Raymond; extensive ashfall and pyroclastic eruptions from Mt. St. Helens begin			
1843		Irrigation begins in watershed		
1847	Oregon Territorial Legislature passes law creating pilotage service; S. C. Reeves is first pilot			
1848	Oregon becomes Territory			
1849	First U.S. Coast Survey initiated in estuary by Lt. Commander William P. McArthur and Lt. Washington A. Bartlett			Second largest spring freshet on record, measured at 31.1-34.0 x 10^3 m^3 s^{-1} at The Dalles
1851	Tansey Pt. treaties with Lower Chinook Indians; only ~8,000 native peoples survive in Columbia River Basin			
1853	Washington becomes Territory		Gillnets introduced to fishery	
1856	First Cape Disappointment Lighthouse completed; cost, $38,000			
1857	Mt. St. Helens ashfalls and pyroclastic eruptions cease			
1859	Oregon State admitted to union			24.6 x 10^3 m^3 s^{-1} spring freshet
1862				26.9 x 10^3 m^3 s^{-1} spring freshet; also 1861-1862 winter flood on Willamette River was largest on record, 8.5 x 10^3 m^3 s^{-1}, with Portland inundated twice during the winter
1864				Moderately strong spring freshet of >21.2 x 10^3 m^3 s^{-1}
1866		First channel dredging	First salmon cannery, built by George Hume and Andrew Hapgood at Oak Pt.; first intensive fishery; 272,000-lb chinook catch	Moderately strong spring freshet of >21.2 x 10^3 m^3 s^{-1}
1867			Hume and Hapgood can 18,000 cases of chinook; fishers paid $0.15/fish	
1870			10,200,000 lb chinook catch	

Year	Historic/Scientific	Hydropower, Irrigation, and Navigation	Salmon	Peak Flow Events
1871				24.4×10^3 m^3 s^{-1} spring freshet
1873			Four canneries operating	
1875	Pt. Adams Lighthouse completed		*Oregonian* reports on 3 March that U.S. Fish Commissioner Spencer Baird predicts that Columbia River salmon fisheries will likely be depleted, like other U.S. and European fisheries, due to overfishing, dams, and habitat loss.	
1876		First scrape dredging of Columbia River entrance bar		27.2×10^3 m^3 s^{-1} spring freshet
1877			Oregon and Washington State Legislatures approve laws to temporarily close fisheries, but provide no enforcement; Oregon/Washington Fish Propagating Co., Clackamas Hatchery begins production	
1878	First lifesaving station established at Fort Canby near present-day Ilwaco, Washington			
1880				25.8×10^3 m^3 s^{-1} spring freshet
1881	Lt. Thomas W. Symons, USACE, maps estuary			
1882				24.9×10^3 m^3 s^{-1} spring freshet; large winter flood on Umatilla River
1883	Transcontinental railroad is completed		55 canneries operating in estuary, canning 629,400 cases (catch of 42,799,000 lb chinook), which is peak chinook harvest	
1885		South Jetty construction begins		
1886			Columbia River Fisherman's Protective Union formed	
1887		T. M. Sullivan Dam built on Willamette River, first dam of significant size in system?	First regulatory board in Oregon, of three members, attempts to supervise fishery; state Clackamas Hatchery production begins	25.5×10^3 m^3 s^{-1} spring freshet

Year	Historic/Scientific	Hydropower, Irrigation, and Navigation	Salmon	Peak Flow Events
1888			Last year that only chinook were caught commercially; federal Clackamas Hatchery production begins	
1889	Washington State admitted to union		Sockeye (blueback), 1,210,000 lb, and steelhead, 1,727,000 lb, begin appearing in catch; state Warrendale Hatchery begins production	
1890			Fall chinook harvest begins; fish commission established in Washington; report to Oregon State Board of Fish Commissioners on juvenile loss in irrigation ditches	Second largest winter flood on Willamette River
1892			Spring and summer chinook runs 95% of canneries; declining numbers of chinook observed; first coho (283,000 lb) harvest	
1893		Snag Island dike built; Cordell Channel flow diverted to North Channel	Salmon prices $1.15/lb; first chum (157,000 lb) harvest; U.S. Fish Commissioner Marshall MacDonald warns Oregon Governor of "disasterous outlook for the future of salmon fisheries of the Columbia"	
1894			Fishermen's Protective Union affiliated with American Federation of Labor	Largest spring freshet on record, measured 24.8 x 10^3 m^3 s^{-1} at the Dalles
1895		South Jetty completed; rock ledge near Astoria blasted	30,254,000 lb chinook catch; state hatcheries at Chinook and Kalama, and private hatchery on upper Clackamus, begin production	
1896			Columbia River Packers' Association formed	Moderately strong spring freshet of >21.2 x 10^3 m^3 s^{-1}
1897			Federal Little White Salmon and Upper Clackamus Hatcheries begin production	Moderately strong spring freshet of >21.2 x 10^3 m^3 s^{-1}
1898	North Head Lighthouse completed			

Year	Historic/Scientific	Hydropower, Irrigation, and Navigation	Salmon	Peak Flow Events
1899		7.6-m (25-ft) navigational channel from mouth to Portland authorized	State Wind, Wenatchee, and Upper Clackamus Hatcheries begin production	Moderately strong spring freshet of 21.2×10^3 m^3 s^{-1}
1900	Native American population has declined by 95%, while Euro-American population has increased to 1.1×10^6	$2,000$ km^2 of Columbia River Basin under irrigation		
1901				6.1×10^3 m^3 s^{-1} winter flood on Willamette River
1902		Dredging across Upper Sands Shoal completed; navigational channel realigned		
1903	Dredge *Grant* arrives in estuary			Moderately strong spring freshet of $>21.2 \times 10^3$ m^3 s^{-1}; 6.6×10^3 m^3 s^{-1} winter flood on Willamette River
1904	Dredge *Chinook* arrives in estuary			
1905		River and Harbor Act of 1905 approves Entrance Project, including South Jetty extension		
1906	Steamships *Charles R. Spencer* and *Bailey Gatzert* race from The Dalles to Portland; the *Spencer* runs the Cascades and wins			
1907				6.0×10^3 m^3 s^{-1} winter flood on Willamette River
1909		Substantial dredging begins in estuary; Grays River channel obstructions cleared	State Bonneville Hatchery begins production	5.5×10^3 m^3 s^{-1} winter flood on Willamette River
1910		Lower Salmon and Swan Falls Dams (Snake River) completed	Hatcheries started rearing (feeding) fry	
1911			36,603,000 lb. chinook catch, but marked decline noted	
1912			Spring and summer run chinook had dropped by 75%	
1913		Extension to South Jetty completed; North Jetty construction begins; Cowlitz River, Oregon Slough, and Baker Bay channels dredged		

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Year	Historic/Scientific	Hydropower, Irrigation, and Navigation	Salmon	Peak Flow Events
1914	1st year of Willis Rich's sampling juvenile salmon	South Jetty extension completed; extensive dredging and pile dike construction begins in river channel		
1916	Last year of Rich's sampling juvenile salmon			
1917		North Jetty extension completed; 9.1-m (30-ft) channel authorized from mouth to Brookfield		
1918-1919				
1920		North Jetty extension completed; 9.1-m (30-ft) channel authorized from mouth to Brookfield	Harvest in obvious decline	
1923				5.6×10^3 m^3 s^{-1} winter flood on Willamette River
1924		Clatskanie River channel dredged	State Klaskanine Hatchery begins production	
1928		Deep River channel cleared; 10.7-m (35-ft) river channel recommended		
1931		South Jetty rehabilitation begins; Lake River channel dredged		
1932	USACE current survey conducted at entrance	Chinook pile dike constructed		
1933		Rock Island Dam completed		
1934	U.S. Bureau of Fisheries begins comprehensive survey of Columbia River tributaries	Ilwaco Channel completed		
1935		10.7-m (35-ft) Columbia River channel completed; dikes along river completed; Harrington Pt., Multnomah, and Cathlamet Channels completed		
1936		Estimated 174 dams in Columbia River Basin		
1937	Bonneville Power Administration (BPA) established			
1938		Bonneville Dam completed; Youngs Bay channel cleared; North Jetty rehabilitation begins		

Year	Historic/Scientific	Hydropower, Irrigation, and Navigation	Salmon	Peak Flow Events
1939		Jetty A, North Jetty rehabilitation and Sand Island pile dikes completed; Skipanon channel and Westport and Elochoman Sloughs dredged	Fisheries biologist Willis Rich predicts rapid "extermination of a large part of the remaining runs of both Chinooks and bluebacks"	
1940		Chinook channel and Astoria mooring basin and breakwaters completed		
1941		Grand Coulee Dam completed; concrete terminal added to South Jetty		
1943				5.9×10^3 m^3 s^{-1} winter flood on Willamette River
1944		Ilwaco Channel completed		
1945		Lois Island created with dredged material; routine annual dredging of entrance initiated		5.2×10^3 m^3 s^{-1} winter flood on Willamette River
1946	USACE initiates research on radionuclides in river, estuary, and coastal ocean			
1947	USGS bathymetric survey of estuary and river begins			
1948		Ilwaco and three pile dikes on Sand Island completed		Third largest spring freshet on record, the "Vanport Flood" measured 28.3×10^3 m^3 s^{-1} at The Dalles
1949	Columbia River Advisory Group (CRAG) formed to advise Hanford operations	Bliss Dam completed (Snake River)		
1950	Flood Control Act of 1950	Astoria East Mooring Basin completed		
1951		Desdemona Shoal Channel realignment		
1952		C. J. Strike Dam completed (Snake River)		
1953		Fourth Sand Island pile dike completed		
1954		McNary Dam completed; River and Harbor Act of 1954 approves 14.6-m (48-ft) entrance channel project		

Year	Historic/Scientific	Hydropower, Irrigation, and Navigation	Salmon	Peak Flow Events
1955		Chief Joseph Dam completed		
1956				
1957		The Dalles Dam completed; Warrenton Mooring Basin dredging and Ilwaco Channel deepening completed		
1958		Brownlee Dam (Snake River) completed; Westport Slough cleared; Chinook breakwaters extended; dredge disposal Site B becomes primary disposal area		
1959	Major USACE-supported circulation study	Priest Rapids Dam completed		
1960		Cowlitz River channel dredged		
1961		Rocky Reach Dam, and Ice Harbor and Oxbow dams on Snake River, completed; South Jetty and Jetty A rehabilitated		
1962	Completion of USACE-WES physical model of estuary; Working Committee for Columbia River Studies formed to focus studies on Hanford radionuclides	12.2-m (40-ft) Columbia River channel to RKm 169 and 18.5 km up Willamette River authorized		
1963	Prototype physical measurements initiated by USACE-WES	Wanapum Dam completed		
1964				5.1×10^3 m^3 s^{-1} winter flood on Willamette River
1965	Radionuclide studies of estuary sediments			
1966	Astoria-Megler Bridge completed; radionuclide studies of Columbia River			
1967	Haertel and Osterberg publish first major scientific paper on biota of the estuary (Ecology 48:459-472)	Wells Dam and Hells Canyon Dam completed (Snake River)		
1968		John Day and Arrow Lake/Keenleyside Dams completed		

Year	Historic/Scientific	Hydropower, Irrigation, and Navigation	Salmon	Peak Flow Events
1969	Haertel et al. publish first significant scientific treatise on nutrient and plankton dynamics (Ecology 50:962-978)			
1970		Little Goose Damcompleted(Snake River)		
1972	Pruter and Alverson's "The Columbia River Estuary and Adjacent Ocean Waters: Bioenvironmental Studies" published as a compilation of USACE studies in the estuary and ocean since 1942			
1973		Mica Lake Dam and Lower Granite (Snake River) dams completed		
1975	USACE current meter studies			
1976		12.2-m (40-ft) river channel completed from entrance to Portland/Vancouver; Oregon Slough deepened		
1977		15.9-m (52-ft) entrance project initiated		
1978	USACE current meter studies			
1979	Initiation of CREDDP investigations			
1980	Mt. St. Helens erupts, with massive mudflows into the Columbia River at Toutle River	31,6000 km^2 under irrigation		
1981	U.S. NOS current meter study			
1982	Coal port channel to Tongue Pt. proposed			
1983		Completion of 5-11 x 10^6 m^3 of material dredged from the Cowlitz/Columbia confluence		
1984	Final CREDDP "Integration Report" published	Revelstoke Dam completed		
1985		Total annual water withdrawal of 13,300 x 10$^{6\ m3}$		
1989		Deepening of 13.1-m (43-ft) navigational channel authorized		

Year	Historic/Scientific	Hydropower, Irrigation, and Navigation	Salmon	Peak Flow Events
1990	Five-year Lower Columbia River Bi-State Water Quality Study initiated		Snake River sockeye and chinook listed under Endangered Species Act	
1992			Snake River fall chinook listed as threatened under ESA	
1994		Feasibility study of dredging navigational channel to 13.1 m (43 ft) begins		
1996	With completion of Lower Columbia River Bi-State Water Quality Study, lower river and estuary become National Estuary Program site (U.S. EPA)			
1997				Strongest spring freshet in 23 years, but only 16.2 $\times$ 103 m^3 s^{-1}
1998			Upper Columbia River spring-run chinook and lower Columbia River steelhead ESU proposed for listing as endangered, and several mid- and lower-Columbia River chinook ESU stocks as threatened, under ESA	
1999	National Estuary Program completes comprehensive management plan for lower river and estuary	USACE approves enviornmental impact statement to deepen the Columbia River navigation channel from 40 to 43 ft.	10-23 $\times$ 10^6 salmon smolts are estimated to be consumed by Caspian terns nesting on Rice Island, an artificial, dredged material disposal island in the middle of the estuary	