The Columbia River Estuary and the Columbia River Basin Fish and Wildlife Program

Independent Scientific Advisory Board
Northwest Power Planning Council
National Marine Fisheries Service
851 SW 6th Avenue, Suite 1100
Portland, OR 97204

Peter A. Bisson
Charles C. Coutant
Daniel Goodman
Robert Gramling
Dennis Lettenmaier
James Lichatowich
Eric Loudenslager
William Liss
Lyman McDonald
David Philipp
Brian Riddell

November 28, 2000
ISAB 2000-5

EXECUTIVE SUMMARY

The Northwest Power Planning Council (Council) requested the Independent Scientific Advisory Board (ISAB) to undertake a review of the impacts of estuarine conditions on the Council's mission to "protect, mitigate and enhance" fish and wildlife in the Columbia River as affected by development and operation of the hydroelectric system. The ISAB agreed to undertake the review but cautioned that it was unlikely that it could quantify the impact of changes in the estuary relative to specific program or management actions taken in the upper river. The ISAB could, however, provide a historical perspective and qualitative assessment of impacts, identify potentially useful collaborations, and provide recommendations concerning future efforts needed to more quantitatively address this issue (letter to Council, Jan. 26, 2000).

While conducting this review the ISAB became aware that there was extensive overlap between a study by the National Marine Fisheries Service (NMFS) and this ISAB assignment. The ISAB expects the NMFS study will add significantly to an informed response to the Council. Consequently, this report has been prepared as a preliminary reply, with additional detail possible following publication of the NMFS study.

Before human influence, the Columbia River estuary was a high-energy environment dominated by physical forces, with extensive sand-beds and highly variable river flows. Several authors have suggested that the biological processes in this environment may have been unique on the Pacific coast. The estuary of today, however, has been extensively modified in terms of physical and biological processes. The development and operation of the hydroelectric system have contributed significantly to these changes. Direct effects have been through changes in seasonal flow rates, reduced sediment discharge, and resultant changes in the estuary's energy balance.

There is extensive documentation about changes in the estuary over the past century. The major changes resulting from development of peripheral wetlands and their isolation from the estuary, development and deepening of the Federal Navigation Channel, and regulation of upper Columbia River flows for hydrosystem needs and flood control. The effects of these changes do not function discretely. The estuary is a complex interaction of physical features (predominated by the energy balance between river flow and tidal forces), resultant changes in circulation, salinity intrusion, sediment processes, and ultimately the biological consequences of these changes. Superimposed on this dynamic environment have been changes in water quality, introduction of exotic species, and the enormous investment in hatchery production of salmonids to mitigate for related losses due to the hydrosystem.

The question of the potential biological impacts associated with these changes is more complicated than detecting the physical impacts. Changes in the biological processes varied from a fundamental alteration in the basis of the food web to the exclusion of sub-yearling chinook and chum salmon from a large portion of the tidal marshes. The effects of these specific changes, however, are difficult to partition from the effects of numerous other impacts in the Basin. Furthermore, our ability to assess impacts of estuarine conditions on the Fish and Wildlife Program has been limited by a lack of appropriate and available data. Information necessary to meet the 1994 Program objectives was simply not acquired for the estuary. Similar obstacles were expressed to the ISAB by the NMFS study team who noted that the data are insufficient to even determine the extent of modern estuarine use by salmonids.

While the ISAB recognizes the limitations of data to directly assess impacts of changes in the estuary on the Fish and Wildlife Program, after our review it is our assessment that these changes have been detrimental to salmonids and the rebuilding objectives of the Program. We base this advice principally on three major issues:

1. The significant loss of peripheral wetlands and tidal channels; these habitats are important to the early rearing, survival and growth of chum salmon, sub-yearling chinook, and smaller coho salmon in other west coast estuaries.
2. The extent of change to seasonal flows following development of the hydrosystem. The affects of these changes are closely associated with the impact of the development of the navigation channel. In combination these developments have resulted in changes to estuarine circulation, deposition of sediments, and biological processes.
3. The need for precautionary advice given the current state of most salmonid populations in the Basin, the magnitude of change in the estuary, and the lack of investigations upon which to base alternative advice.

As the 2000 Fish and Wildlife Program is developed, the ISAB recommends an aggressive experimental program targeted to reduce the likelihood of prolonged uncertainty about the impact of estuarine conditions. Such a program should incorporate monitoring of the physical environment (such as currently begun via the CORIE program, Oregon Graduate Institute) combined with evaluation of large-scale manipulations of estuarine habitats. The intent of these manipulations would be to study changes presumed to have had negative impacts and to conduct these at a scale that can be measured within the natural environment. These types of programs would be consistent with the vision statement in the 2000 Fish and Wildlife Program:

> "Wherever feasible, this program will be accomplished by protecting and restoring the natural ecological functions, habitats, and biological diversity of the Columbia River Basin."

The types of large-scale programs that are envisioned include:

a) removal of dykes in the lower river and upper estuary to restore connections between peripheral floodplains and the river or fluvial zone of the estuary;

b) actively managing sources of salmonid predation in the estuary through restoration of natural habitats, removal of habitats artificially created due to channel construction and/or maintenance, or controlling predator populations.

c) establish an allocation of water within the annual water budget for the Basin, that would simulate peak seasonal discharge, increase the variability of flows during periods of salmonid emigration, and restore tidal channel complexity in the estuary (aided by removing pile dykes where feasible).

Initially, we anticipate that people will think that such programs are unnecessary and/or impractical. To achieve the vision statement of the 2000 Fish and Wildlife Program in the estuary province, however, programs of these magnitudes are likely necessary given the magnitude of the estuary and the stated desire to evaluate these actions. The Columbia River estuary is the interface between a highly modified freshwater system and the open ocean environment. All of the investment and effort in the Fish and Wildlife Program flow through this unique environment, but interaction of change in the estuary with projects of the Fish and Wildlife Program, and their combined effect, has basically been ignored. The ISAB strongly recommends that the Council recognize the potential value of the estuary to the Fish and Wildlife Program and the immediate need to improve our understanding of its ecological processes.

TABLE OF CONTENTS

The Columbia River Estuary and the Columbia River Basin Fish and Wildlife Program

Introduction

The Northwest Power Planning Council (Council) requested the Independent Scientific Advisory Board (ISAB) to undertake a review of the impacts of estuarine conditions on the Council's mission to "protect, mitigate and enhance" fish and wildlife in the Columbia River as affected by development and operation of the hydroelectric system. The ISAB agreed to undertake the review but cautioned that it was unlikely that they could quantify the impact of changes in the estuary relative to specific program or management actions taken in the upper river. The ISAB could, however, provide an historical perspective and qualitative assessment of impacts, identify potentially useful collaborations, and provide recommendations concerning future efforts needed to more quantitatively address this issue (letter to Council, Jan. 26, 2000).

Since undertaking this assignment, the ISAB has reviewed an extensive literature about the estuary, toured the estuary (July 2000), and met with a National Marine Fisheries Service (NMFS) study team (June 2000) that is presently completing a major investigation of the estuary and its linkages with Pacific salmon. The latter study was developed in response to the 1996 Amendment to the Northwest Power Act of 1980 and the 1997 Council paper (NWPPC 1997) on consideration of ocean conditions in the Fish and Wildlife Program. That study is the first holistic consideration of salmon and their estuarine ecosystem and the potential effects of upstream development on this linkage. The NMFS study documents historical changes in the estuary, develops new conceptual models that include application of new data linking these physical changes to biological diversity in Columbia salmonids, and will evaluate management strategies to improve estuarine conditions for salmonids. Furthermore, a team of researchers with extensive knowledge of this estuary (see Small 1990) is conducting that study, and there is extensive overlap between the NMFS study and the ISAB assignment. The ISAB expects that the results of the NMFS study would add significantly to an informed response to the Council. Consequently, this report has been prepared as a preliminary reply, with additional detail possible following publication of the NMFS study.

Literature concerning the estuary is extensive[1] but the vast majority of the work concerns specific species or questions and spans short time periods. There had not been a coordinated publication of physical and biological characteristics of the estuary until the Columbia River Estuary Study Taskforce (CREST) report (Seaman 1977) or a comprehensive research program until the Columbia River Estuary Data Development Program (CREDDP 1978-1981, see Simenstad et al. 1984). The latter describes the estuary at the ecosystem level of organization and integrates the final reports of 13

---

[1] Morgan et al. (1979) and CREDDP (1980) provide other useful literature surveys and annotated bibliographies concerning investigations before 1980. Costello (1996) relates references to Pacific salmon and the Columbia River estuary to Measure 7.1A of the Council's 1994 Fish and Wildlife Program.

CREDDP work groups or topics. The data collected during CREDDP has been extensively used in many subsequent publications because no other large-scale ecosystem level program has been undertaken since. Simenstad et al. (1984) is a large, two-volume compendium of CREDDP results but more concise publications providing excellent overviews are Small (1990) and Simenstad et al. (1992). The journal volume edited by Small (1990) consists of ten journal papers dedicated to the physical, chemical, and biological characteristics of the Columbia River estuary and historical changes to the estuary over the past century. In that volume, Sherwood et al. (1990) conclude that changes in the estuary, as well as changes in the fluvial part of the system, have contributed to the dramatic decline in salmon populations in the Columbia River.

The Estuary Environment

In common use, an estuary may be considered the portion of a river that is influenced by ocean tides. Neal (1972) identified three different influences of tides:

1. The maximum distance upstream at which tidally induced water-level fluctuations are observed.
2. The maximum distance upstream at which tidal inflow causes the river flow to reverse.
3. The maximum distance upstream at which measurable amounts of seawater are found.

In the Columbia River, tidally induced changes in water level are observed as far upstream as Bonneville Dam (RM[2] 146) during low river flow, and reversal of river flow has been measured as far upstream as Oak Point (RM 53). Intrusion of saltwater is, however, generally less than 23 miles (near Harrington Point) at the minimum regulated monthly flow (Neal 1972), although when lower daily flows occur, salt intrusion can extend past Pillar Rock (approx. RM 28).

The area influenced by the intrusion of saltwater is most consistent with technical definitions of an estuary.

> “An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage.” (Lauff 1967)

The CREDDP study, however, included about 46.5 miles (75km) of the river-estuarine continuum, stretching from the river mouth to approximately 20km above the maximum extent of salinity intrusion during low river flows (Simenstad et al. 1990, see Figure 1). Although it is unlikely that the upriver extent of this area ever receives saltwater, it is likely that the area would be influenced by the [salt?] intrusion and reversal of river flow on a daily basis. The area examined then includes the true estuary plus the area likely to be influenced biologically by ocean tides.

---

[2] Distance along the Columbia River is measured by the convention of ‘River Miles’ used to indicate distance up-river from the ocean entrance of and along the navigation channel (Simenstad et al. 1990)

Figure 1. Basic map and bathymetry (circa 1980) of the Columbia River estuary (Simenstad et al. 1990). Places named in the report are shown. The convention of river miles upstream is shown as distance upstream of the river mouth and through the navigation channel (RM = 0 at outer margin of the north and south jetties).

The Columbia River estuary region (defined in this text as the CREDDP study area) is a large, high-energy environment (strong tidal currents and large river flows) with high temporal variability in circulation, sedimentation, and biological processes (Sherwood and Creager 1990, Jay and Smith 1990, Jay et al 1990).

Two estimates of the surface area and habitats in the Columbia River estuary exist (Thomas 1983, Simenstad et al. 1984). Both estimates used the same basic data (1958 NOAA bathymetric survey), but employed slightly different definitions for habitat strata. Overall, however, the analyses are similar (range of areas from 412 to 482 sq. km.) and actually only differ substantively in their estimates of area in tidal flats (Table 1). Based on maps outlining the areas surveyed in these two reports, it seems that Thomas (1983) included more area in the peripheral bays than the Simenstad et al. (1984).

Table 1. Estimates of the total surface area in the Columbia River estuary by habitat type, based on the 1958 NOAA bathymetric survey. Areas estimated by Thomas (1983) and CREDDP (Simenstad et al. 1984) were expressed in different units and have been converted to (sq. km.) for comparison (1 sq. mi. = 2.59 sq. km.)

Habitat type	Thomas	CREDDP	Comments
1) Deep Water (area below 18' depth)	131.8	122.2	Reports used same definition, CREDDP designated this habitat as Channel Bottom
2) Medium depth or Demersal slopes	104.1	130.8	CREDDP defined stratum down to 3' below mean low low water, but Thomas used 6' below MLLW[3].
3) Tidal flats and shallows	181.2	99.6	Difference associated with comment above.
4) Tidal marshes	37.2	28.5	CREDDP defines down to 3' above MLLW but Thomas used MLLW as boundary.
5) Tidal swamps	28.1	30.8	Discretion in defining upper boundary of tidal marshes.
TOTAL	**482.5**	**411.8**	Difference associated with areas in peripheral bays that were included.

While the Columbia estuary is a large, highly dynamic environment, three other features differentiate it from other major estuaries and are important within the context of the Fish and Wildlife Program. First, while changes in estuarine habitats will be noted, overall the Columbia River estuary is substantially less disturbed than other large westcoast estuaries

---

[3] Diurnal tides are not equal in strength, consequently there will be two levels of low and high tides per day. The designation of a low low water is the lower water height of the two low tides in a day. The Mean low low water is the average height of the lower of the two daily low tides over a specific time interval. By definition, the elevation of the MLLW is set to zero.

(see Nichols et al. 1986, Sacramento-San Joaquin; and Northcote and Larkin 1989, Fraser River, BC). For example, while the upper Fraser River is certainly not as disturbed as the upper Columbia River, the lower Fraser River and estuary is highly channelized, with extensive loss of wetlands and major urban development along the lower 100 km of the river. Second, river flows in the Columbia River are now highly regulated and different from its historical flow pattern. The extent of flow regulation and its interaction with tidal energy are closely related to changes in physical and biological features of the estuary (Jay et al. 1990). Third, the extensive development of the lower Columbia River for shipping and the use of jetties and dredging to stabilize dredged channels have altered the physical environment of the estuary. Sherwood et al. (1990) provides a concise history of these developments but the scale of the dredging activity alone is informative. These authors estimate that between 1909 and 1982 dredging operations each year removed one-third to one-half of the annual fluvial sediment supply to the estuary!

Although it is convenient to discuss individual features or changes in the estuary, essentially all of these changes interact. Some may interact to amplify impacts while others may compensate. For example, regulated river flows now substantially reduce the peak freshet flow and reduce sediment input to the estuary. Channel dredging though concentrates flow in a main channel and reduces flows in the peripheral areas, allowing greater retention of sediments in those areas. These interactions become increasingly complicated, especially when their effects on biological processes are considered.

While this report will focus on the Columbia River estuary region, we should note that the river habitats upstream to Bonneville Dam are also certainly important to salmon. This area of the lower Columbia River has been classified into habitat categories in a manner comparable to Thomas (1983). Graves et al. (1995) reported on these habitat categories for the river and estuary downstream from Portland (Table 2).

Table 2. Historical habitat area (circa 1880) and classifications for the lower Columbia River based on Thomas (1983, Columbia estuary region) and Graves et al (1995, up-river of estuary to Portland), data are presented in acres (1 acre = 4047 sq.m. = 0.004 sq.km.).

Habitat categories	Columbia R. Estuary	Lower Col. R. above estuary
Medium and Deep water	69,350	43,967
Sub-tidal and flats	40,640	4,237
Tidal marsh and swamps	46,200	13,753
Non-tidal wetlands	50	29,645
Uplands, non-tidal	1,930	17,676
Total Area (acres)	158,170	109,278

Historical Changes to the Estuary

Changes to Estuary Habitats

Two significant assessments both indicate a loss of estuary habitat area but the extent of change is highly dependent on the location in the estuary and the type of habitat. For example, Thomas (1983) reports major loss of tidal marsh and swamp habitats, but Cathlamet Bay was much less disrupted than other peripheral bays and the upper estuary. Combining the Sherwood et al. (1990) analysis with Thomas' estimate for tidal marsh and swamps results in an **overall estimate of estuary habitat loss of 25% (by area)** between 1868 and the 1958 USGS survey.

A rich archive of maps, bathymetric charts, photographs and notes about the estuary in the later 1800s and early 1900s permit comparison of the present estuary with habitats that existed before most development occurred. After examination of these materials, Thomas (1983) selected charts issued by the U.S. Coast Survey for 1868-1873 as the best available representation of undeveloped estuary and compared these charts to the 1958 NOAA bathymetric survey. The historical records allowed Thomas to define five habitat types listed in Table 1.

1) Deep Water: surface areas below the eighteen-foot bathymetric contour.
2) Medium depth Water: surface areas for water between the 18' contour up to the six-foot contour.
3) Shallow and tidal flats: surface areas shallower than the 6' contour up to the edge of tidal marsh or swamp vegetation, or the mean higher high water level if vegetation mappings were absent.
4) Tidal marshes: areas dominated by emergent vegetation or low shrubs, and found from MLLW too slightly above MHHW.
5) Tidal swamps: shrub and forest dominated wetlands extending up to the line of non-aquatic vegetation (these swamps may only be inundated during spring tides but they also extend down to MHHW).

Thomas estimated a 24% reduction in overall surface area of the estuary with the greatest change occurring in the shallow water and shore-land habitats (Table 3). If only change in the latter habitats is considered, then the proportion of habitat lost over time increases substantially. Thomas provides a detailed description of habitat changes by sub-areas and the processes involved both natural and human induced. The largest single factor involved in these changes has been dyking of low elevation wetlands in the peripheral bays and upper estuary fluvial sub-area. Dykes remove areas entirely from the estuarine system, and reducing surface area and water volume, rather than change areas from one habitat type to another. Thomas identifies shoaling as the second most important cause of change and notes the increase in shallow water and tidal flat habitats. The vast majority of this increase, however, occurs in one sub-area (Baker Bay) followed by much smaller increases in the upper estuary habitats.

Sherwood et al. (1990) conducted an analysis similar to Thomas (1983), but focused their assessment on sub-tidal areas. Estimates of "surface area" in several depth strata were made using bathymetric charts for three survey periods: 1867-1877, 1926-1937, and 1949-1958 (corresponding to the 1868, 1935 and 1958 U.S. Coast Survey charts). This analysis was a more in-depth assessment of changes in the water column than was possible with the resolution of habitat types used by Thomas (1983).

Table 3. Past and present estuary habitat types and surface area as estimated by Thomas (1983). Area is expressed in acres, 1 acre = 4046.9 square meters.

Habitat type	Pre-development	1958 survey	% Change or Comment
Estuarine Habitats:			
Deep Water	35,140	32,580	loss of 7.3% of area
Medium Depth Water	34,210	25,720	loss of 24.8% of area
Shallows & Flats	40,640	44,770	gain of 10.2% of area
Tidal marsh	16,180	9,200	loss of 43.1% of area
Tidal swamps	30,020	6,950	loss of 76.8% of area
Total	**156,190**	**119,220**	loss of 23.7% of total area
Non-Estuarine habitats:			
Developed Floodplain	0	23,950	Diked floodplain in use for agriculture, residential, or other.
Uplands	1,930	7,590	Natural or filled uplands, mostly through disposal of dredge material.
Wetlands	50	7,410	Areas of undeveloped, dyked floodplain or reverted to wetlands that remain separated from the estuary.

Sherwood et al. (1990) reported that a shift from shallow sub-tidal to greater depths was apparent between 1868 and 1958. Much of the shift was accounted for in the Entrance area to the estuary but similar trends were also evident in the South Channel (southern navigation channel) and in the Upper Channel area (upper estuary fluvial area). In contrast, Baker Bay and Cathlamet Bay sub-areas have filled more uniformly. Sherwood et al. (1990) concluded that the net effect of these changes has been to reduce the surface area of the estuary, while shifting a larger percentage of the sub-tidal area and water volume to deeper water habitats.

Columbia River Flow Regulation

Many of the physical, and indirectly the biological, features in the Columbia estuary are strongly effected by the energy balance between ocean tides and river flow (Jay et al. 1990). As most people are aware, however, development upstream of the estuary has been extensive, and river flows have been altered substantially. Sherwood et al. (1990) provided a concise description of changes in river flow that were due to reservoir storage (between 1933 and 1982, 21 large dams on the Columbia and Snake rivers were built), irrigation for interior basin agriculture, and climate change. Information presented below is similar in content to their report but up-dates the flow data through 1999 (data provided by David Jay and Pradeep Naik, Oregon Graduate Inst., pers. comm.).

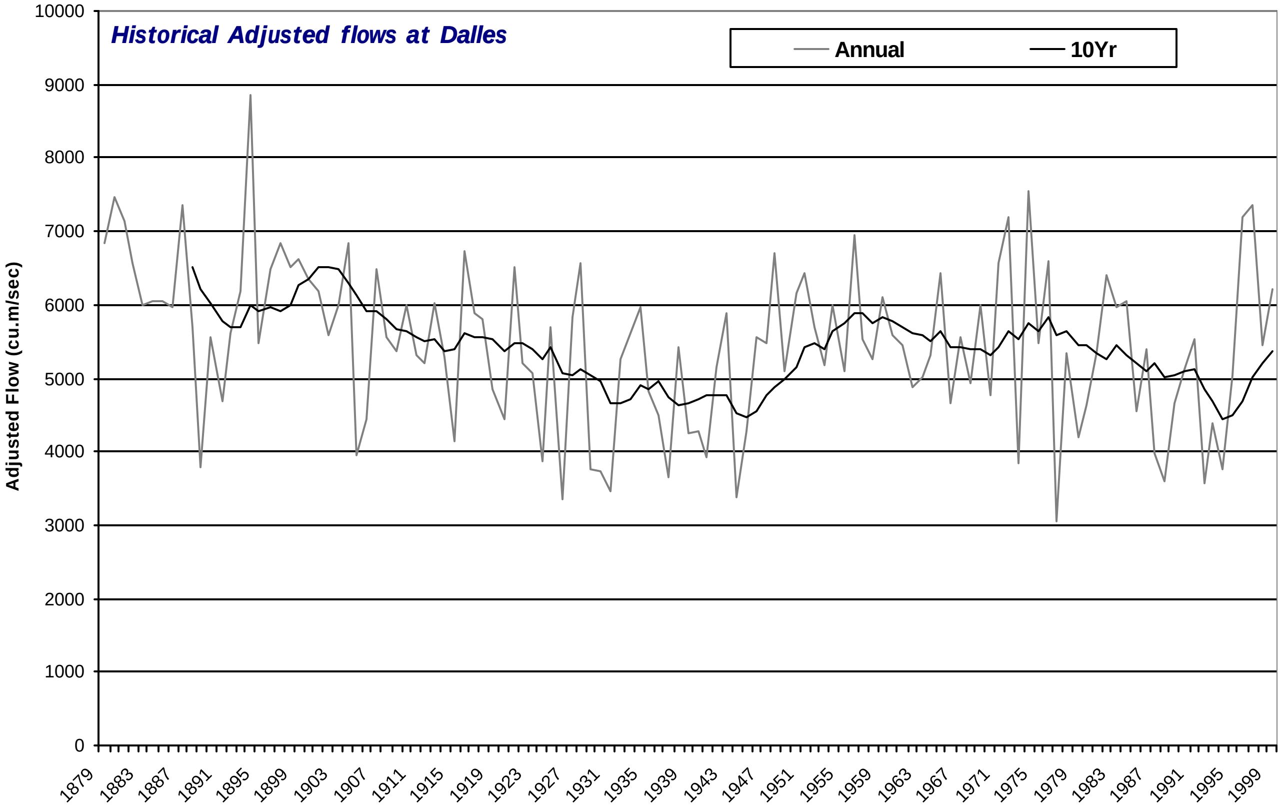
To summarize the changes in Columbia River flows:

a) annual flows measured as the adjusted flow at The Dalles, OR have decreased by approximately 15% relative to pre-1900 river flows;
b) regulation of flows in the upper Columbia became significant about 1969 and has greatly reduced the average flows in the spring freshet (-50 to 55%) and increased the flows in the winter months (+35% October through March);
c) flow from lower Columbia drainages contribute substantially to winter flow conditions into the estuary but in the pre-regulated flow period did not contribute much to the spring freshet or summer flow;
d) since increased flow regulation in the upper river, the lower Columbia drainages are more important as a source of water but spring and summer flows are still dominated by upper river flows;
e) this analysis did not fully examine changes in maximum or minimum flows, or the temporal variability of flows.

Since June 1878, daily flow in the Columbia River has been recorded at The Dalles, Oregon. To examine annual variability and time trends, these data have been summarized as annual average flows (Fig. 2). In using this long time series of flows, however, some of the observed flows will be unregulated (pre-development) and others regulated. To account for this change, ‘adjusted’ flows were estimated for the years with regulated observed flow data. Adjusted flows are the natural flows that would have been expected in a year if the effect of storage was removed (Orem 1968).

Although Figure 2 includes fifteen years of daily flow data added to the analysis presented by Sherwood et al. (1990), the results are very similar; except for a second period of very low flows from the mid-1980s to mid-1990s. Overall, there is approximately a 15% reduction in average annual flow from the late 1800s until the late 1900s (a little less than indicated by Sherwood et al. 1990). The variability in average flow between years, however, often seems at odds with this degree of average change. The NMFS study team will be examining the variability of flows in much greater detail.

Figure 2. Time series of average annual flow (cu. m/sec) for the Columbia River at The Dalles, 1879-1999. Flows have been corrected for the effect of storage (adjusted flows) and the smoothed curve was estimated as a 10-year moving average.



Historical data for Columbia River flows at The Dalles, OR (USGS station gauge 14105700) were also used to examine changes in annual flow profiles by month. Flows averaged by month over years were compared for two periods: flows through 1968 and those after. Sherwood et al. (1990) noted that reservoir capacity doubled in the Columbia basin between 1967 and 1975 providing the capability to dramatically alter flow pattern. Before completion of the Grand Coulee Dam, however, the observed and adjusted flows were equal. To demonstrate the change in adjusted and observed flow, Figure 3a presents average monthly flow between 1941-1968, and Figure 3b compares flows between 1969-1999. Figure 4 expresses the difference in observed minus adjusted flows as a percentage of the observed average flow by month for the period of regulated flows, 1969-1999.

The magnitude of change in monthly flow from the upper Columbia River is apparent in Figure 4. During spring freshet months (May-June), regulated flows have, on average, been reduced by 50-55%. During the winter period (October through March) regulated flows have, on average, been increased by 35%.

Figure 3a. Observed and adjusted river flow (cu. m/sec) for the Columbia River at The Dalles, OR 1941-1968. The similarity of these curves demonstrates that average monthly flow was not altered much by storage capacity or regulation during this period.

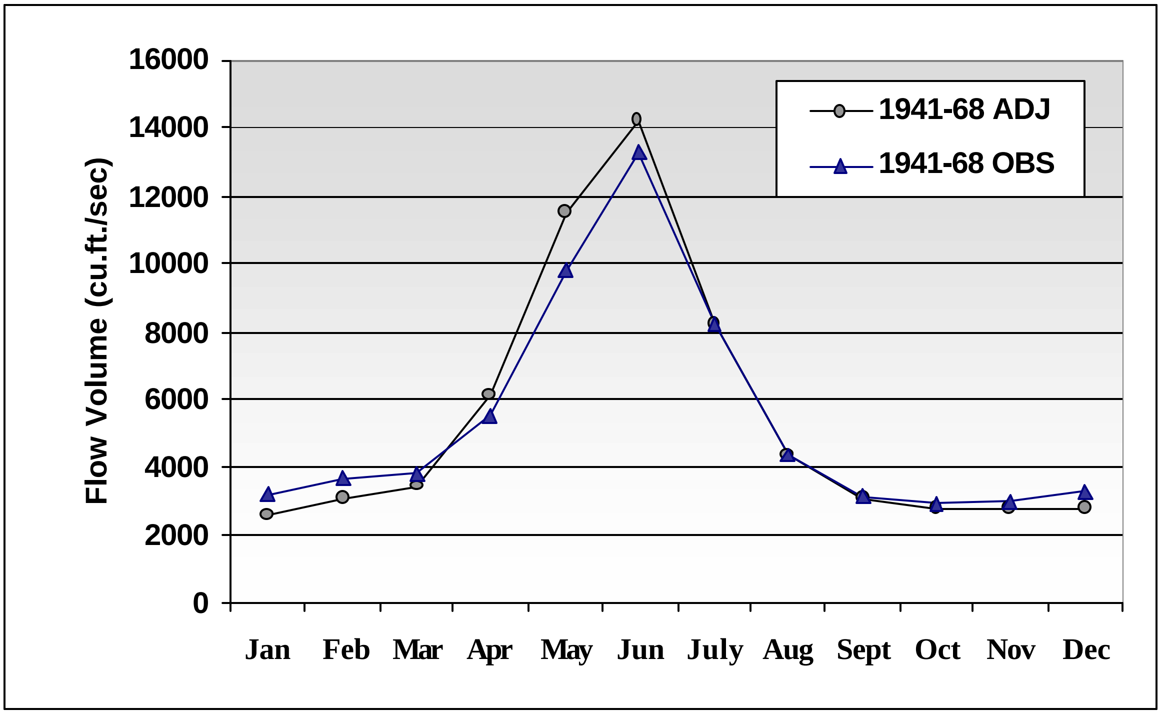


Figure 3b. Observed and adjusted river flow (cu. m/sec) for the Columbia River at The Dalles, 1969-1999. In this period, spring freshets in May, June, and July were greatly reduced and flows in other months increased.

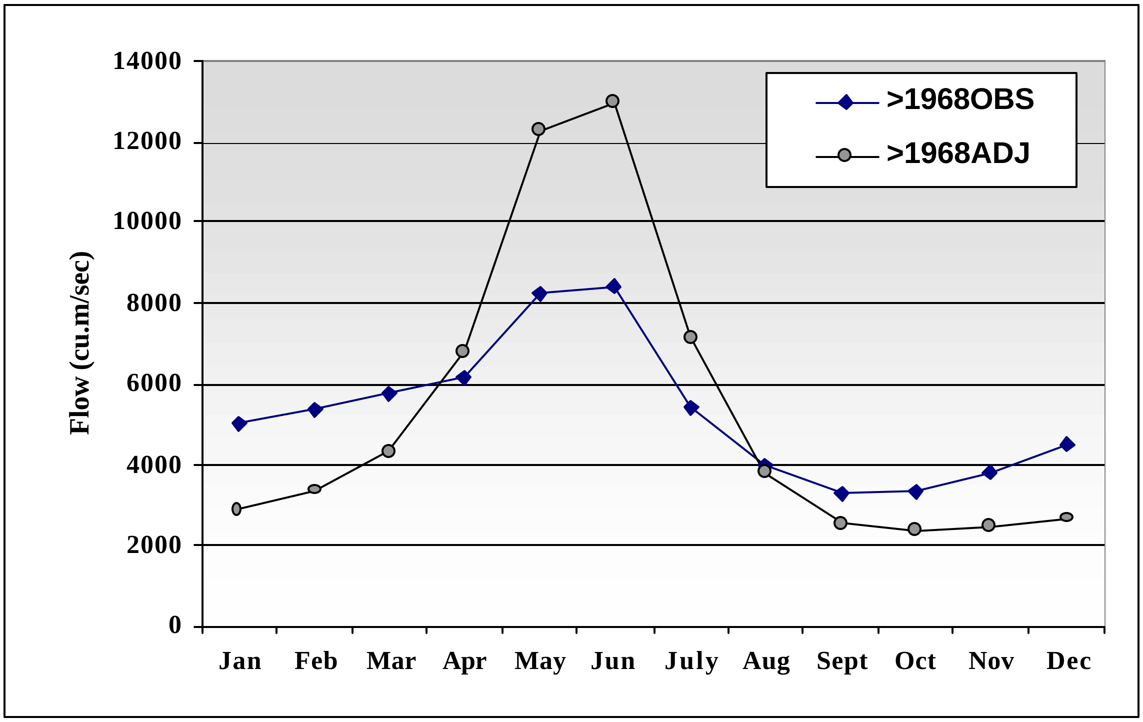
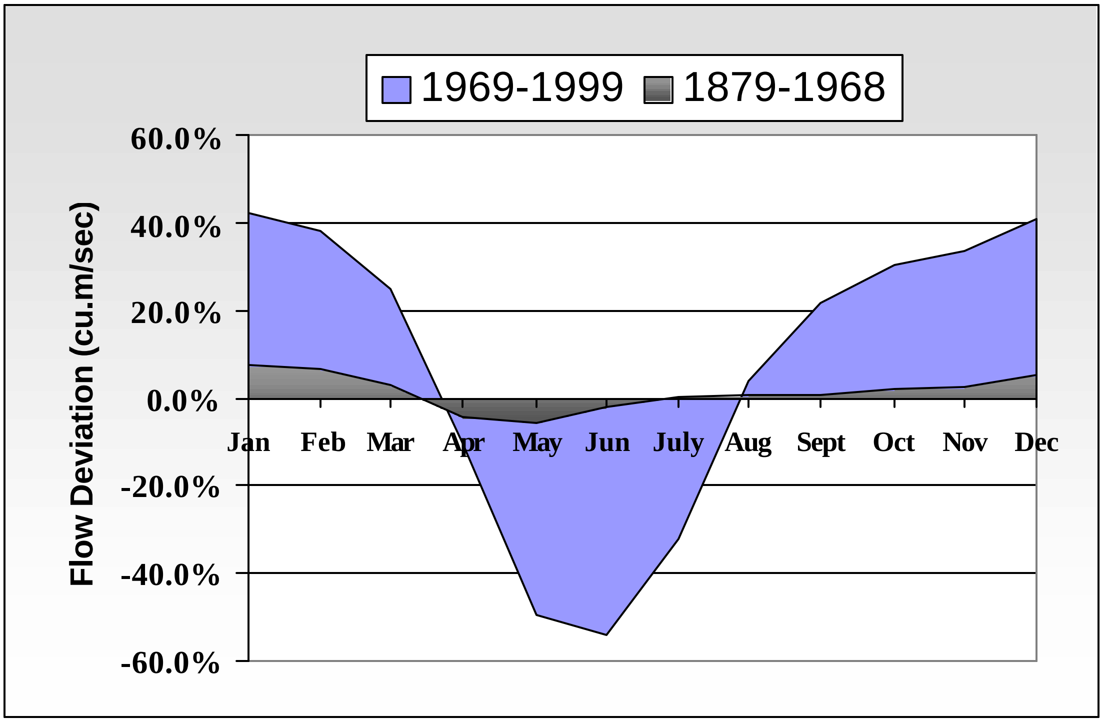


Figure 4. Differences between Observed and Adjusted flows in Figure 3b expressed as (Observed – Adjusted)/Observed flows (% change relative to Observed flow by month).



While these changes are significant, they do not indicate the monthly flow profile observed in the Columbia River estuary since they are measured at The Dalles. Flows in the estuary result from up-river input plus inflow from rivers in the lower Columbia River. The contribution of lower Columbia drainages to flow in the estuary is observed by contrasting flow at The Dalles with flow near the mouth of the Columbia River, both before (Figure 5) and following (Figure 6) significant regulation. Prior to regulation, flow from lower Columbia drainages appears especially important during the winter period but has little effect, on average, during the spring freshet and summer period (Figure 5). To examine regulated flows, the observed flow (cu. m/sec) for the USGS gauge (#14246900) at Beaver Terminal (RM 53.8) in the lower Columbia River[4] was compared to the observed flow at The Dalles (from Figure 3b) for the period 1969-1999 (Beaver Creek data provided by D. Jay and P. Naik, Oregon Graduate Inst). The monthly mean observed flow at Beaver Terminal shows the continued importance of the lower Columbia drainages during the winter months (as in Figure 5). It also indicates that an increased portion of the flow occurs during spring and summer months (Figure 6), and illustrates the major reduction in spring freshet from up-river.

---

[4] River drainages that flow directly into the estuary are relatively small drainages and contribute only a few per-cent of the annual Columbia River flow. However, they may have important localised effects.

Figure 5. Adjusted flow (cu. m/sec) expected at the mouth of the Columbia River, near Astoria OR (squares, data from Orem 1968 and Seaman 1977) compared with the adjusted flow of the Columbia River at The Dalles (circles, data from Figure 3a, <1969ADJ data). The early period data was used in this comparison since the data for the Col. R. mouth was for the period 1928-1968 (data converted from cu.ft/sec).

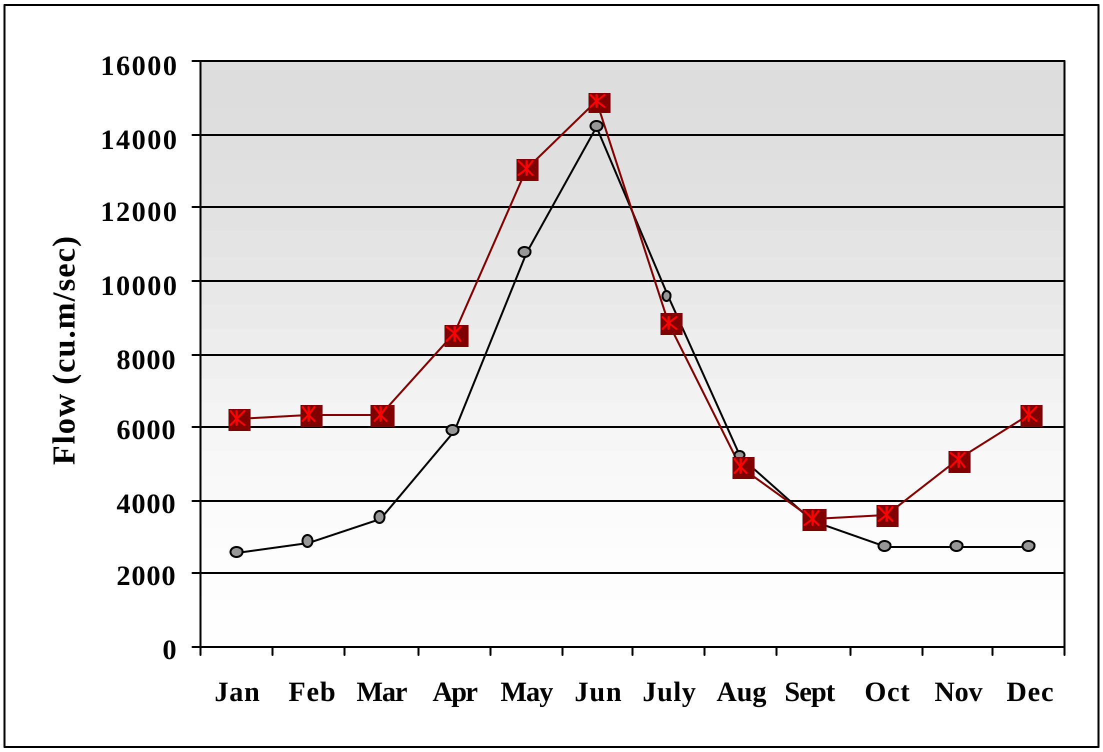
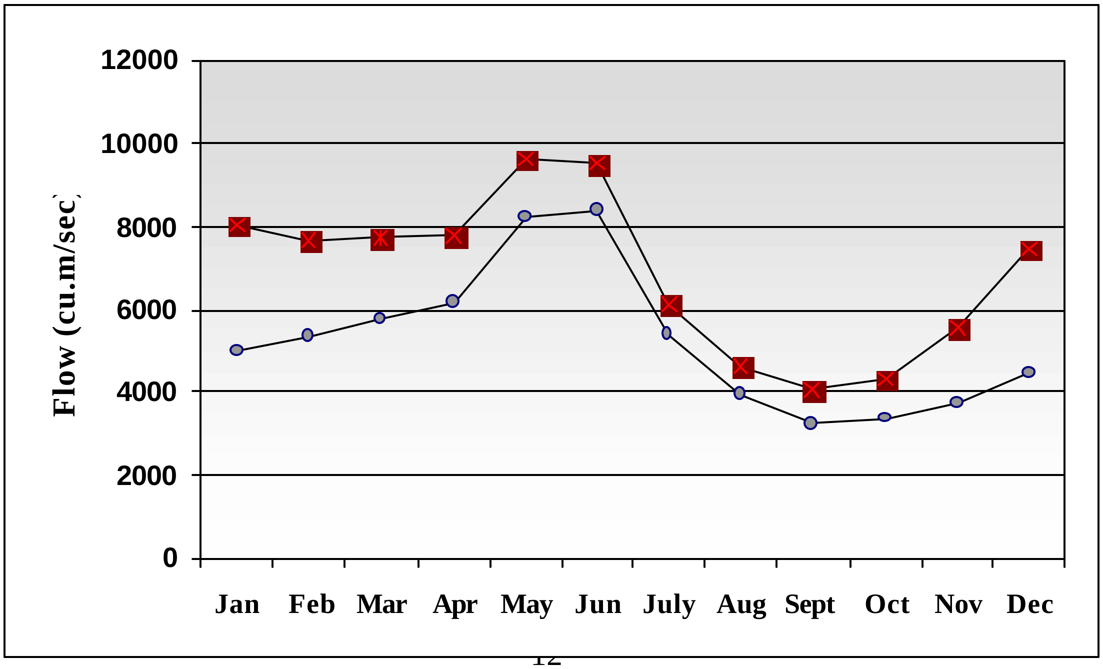


Figure 6. Observed Columbia River flow (cu. m/sec) at the Beaver Terminal compared to the observed flow in the upper Columbia River at The Dalles, average monthly flow for 1969-1999. Beaver Creek data = squares, The Dalles = circles.



The presentation of flow data in these simple comparisons of mean annual or monthly flows do not portray the full degree of change in flow patterns that have occurred. For example, regulation of flow has greatly reduced peak or maximum flows, slightly increased minimum flows, and significantly reduced variability of flows (measured as the co-efficient of variation).

These changes can also be significant in their effect on the estuary habitats due to reductions in sediment transport or reduced flooding of wetlands. Because a complete analysis of flow variability and peak flows will not be included in this report, readers are referred to Sherwood et al. (1990) until the NMFS analyses that are currently being completed area available.

Sediment Loads and the Federal Navigation Channel

The transport of sediments by the river and the morphology of the estuary have both been substantially changed over the past century. The supply of sediment to the estuary is a function of the type of sediments available to the river (e.g., fine clays versus larger sand particles) and river discharge. The deposition of sediment in the estuary results from the balance between fluvial and tidal energies, and morphology of the sediments is a function of circulation in the estuary. Changes in the sources of sediments and regulation of up-river flows makes these considerations complicated … but the added development of the shipping channel makes this situation even more so. Recent analyses of sediment loads in the Columbia River indicate about a 50% reduction in annual average sediment load relative to the pre-dam period. Physical changes in the estuary and regulation of river flow have also altered the dynamics of seawater intrusion, circulation, and sedimentation processes in the estuary.

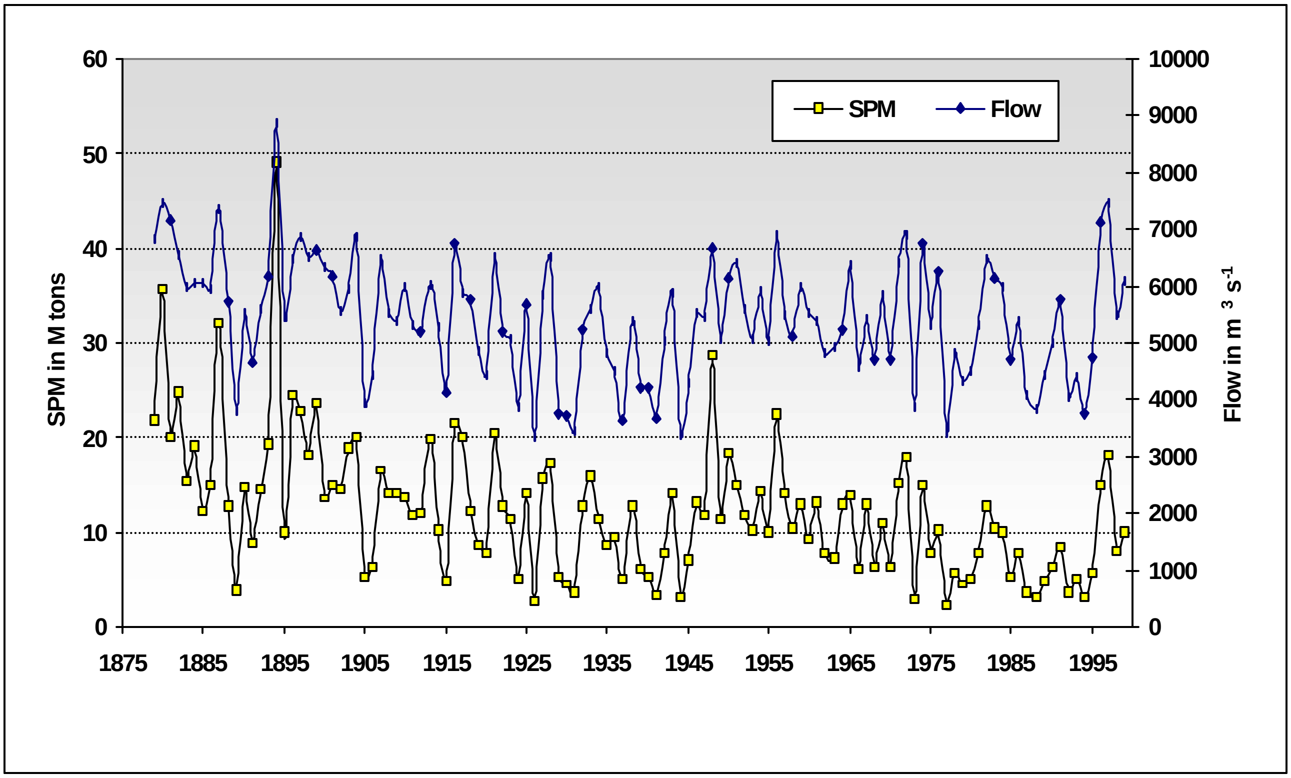
Assessing a change in sediment carried by the river is much less certain than examining the change in river flow. Sediments entering the river depend on the land-use practices and development, historical river flows, and basic soil types or geology. Sediment loads in the river before major development are not known. Sherwood et al. (1990), however, used the limited sediment discharge estimates that were available plus the historic flow data (at The Dalles OR) to back-calculate sediment loads into the late 1800s. For the period 1868 through 1934 (until the first Columbia River dam), they estimated an annual sediment discharge rate of 14.9 million tonnes per year. They contrasted that estimate with more recent flows (for 1958-1981) and report a decrease in average sediment discharge of nearly 50% to 7.6 million tonnes per year.

Recently, D. Jay and P. Naik (Oregon Graduate Institute) have re-examined relationships between sediment load and flow (cu. m/sec), reconstructing the historical sediment loads as reported in Sherwood et al. (1990). Their methods and calculations will be included in the NMFS study report, but they provided these data to the ISAB up-dated through 1999. For the pre-dam period (1879-1935) the estimated annual total sediment load averaged 15.1 million tonnes/year but decreased to 9.7 million tonnes/year between 1936 and 1999. If only the period following completion of the hydrosystem is included (1975-

1999) then the annual average flow is reduced to 7.3 million tonnes/year; a 51% average reduction relative to the pre-dam period (Figure 7).

Recently, the U.S. Army Corp of Engineers (1999) has also estimated annual sediment loads for the period 1980 through 1995. Their estimate of sediment volumes is much lower than Jay and Naik's and is largely based on an assumption that sand supply to the lower Columbia River has been substantially reduced due to the dams. This seems to be a reasonable assumption except that observations in the past four years annual discharge and tonnes of sediment have increased over the 1975-1995 period (Figure 7).

Figure 7. Annual sediment transport (millions of tonnes per year) and flow (cu. m/sec) of the Columbia River at The Dalles, 1879-1999. Sediment transport back-calculated by P. Naik (Oregon Graduate Institute).



The number of years with actual data used in any of these comparisons is very limited and variation between years could be very high for several reasons: development of the hydrosystem during observations, annual variation in climate, number of dams developed and patterns of flow control, location of sampling, etc. What is important, however, is the magnitude of the reduction. Average annual sediment input to the estuary has likely declined over 50% following development of the upper Columbia and flow control.

Two mechanisms are noted as the principal causes of this decline: storage capacity of the reservoirs and reduction in peak flow discharges. To our knowledge, the effect of the reservoirs has not been quantified but the reduction of flow through them must allow larger suspended material to settle out, and restrict any bedload transport (movement of sediment along the riverbed when energy is sufficient). The reduction in peak flows, however, is known to greatly reduce the river's capacity to transport sediment and especially sand (Jay et al. 1990). Flows are usually sufficient to transport fine sedimentary material (silts, clay, and fine sands) but this material may be supply limited, whereas sand is usually capacity limited (Sherwood and Creager 1990). Sandy material may be available but the capacity of the river to transport sand is limited by discharge. The capacity of water to transport sediment increases as a power of the flow discharge and at higher discharge sand constitutes a greater portion of the sediment carried. Before regulation, peak flow events would have provided a very large portion of the sand transported into the estuary. With regulated flows, however, the reduction in sand transported to the estuary is disproportionately greater than the changes in flow and total sediment load.

The proceeding analyses and Figure 7 only address sediment from the Columbia River above the Willamette River. The Willamette and other lower Columbia rivers also provide sediment but their input will not compensate for the estimated 50% reduction from the upper river. Except for an unusual event such as the eruption of Mount St. Helens in 1980 that produced an estimated 250 million tonnes of sediment in one year.

Within the estuary, the distribution of sediment is closely related to the energy balance between ocean tides and river flows. Jay et al. (1990) evaluated an energy budget for the estuary and defined three regions within the estuary based on differences in energy balances, and consequently, sedimentary properties. The lower estuary (downstream of about Rm13) is dominated tidally, the upper fluvial region (above about Rm35) is dominated by river flow, and the intermediate region[5] where both tidal and river processes are important but their energy inputs are much weaker than in either other region. As fluvial energy decreases in the intermediate zone the capacity for sand transport decreases and sand is deposited. The region is also associated with a zone of maximum turbidity that entrains and concentrates fine sediments, detritus and food particles, and feeding organisms (Simenstad et al. 1990). The location and strength of the maximum turbidity is associated with the extent of salinity intrusion (tidal energy) and its upstream extent limited by fluvial energy gradients (river flows).

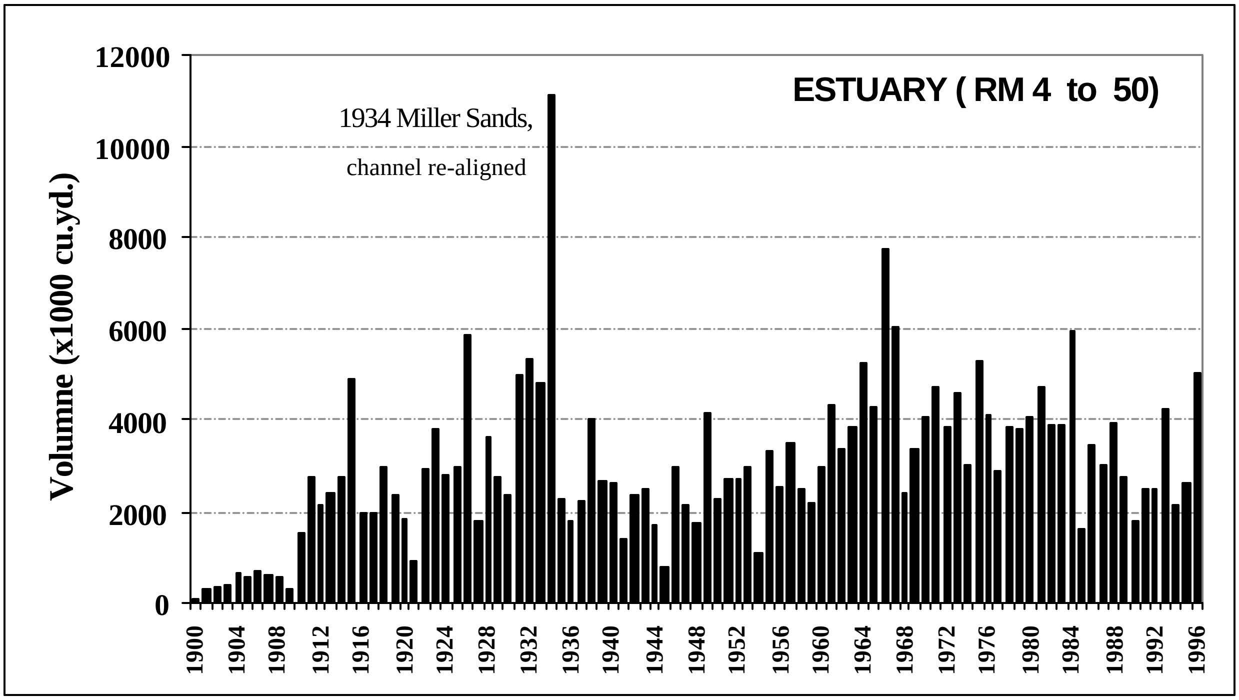
Sherwood et al. (1990) suggest that "effects of human alterations of estuarine flow patterns on the turbidity maximum have had large ecosystem-level consequences." These alterations involve changes to flow and sediment loads (as discussed above) and changes in the estuary morphology associated with jetties, dyking, and development of the shipping channel. Construction of the Columbia and lower Willamette River navigation channels was authorized in 1878 with a minimum depth of 20 feet. However, over the next 100 years the channel was expanded to a 40 ft depth and 600 ft width (US Corp Engineers 1999). To develop and maintain these channels large sediment volumes are dredged annually (Figure 8) and 236 pile dikes have been built throughout the channels to focus flows, reduce erosion, and provide disposal sites. Dredged materials

---

[5] This region is referred to by Jay et al. (1990) as the energy flux divergence (EFD) minimum region.

are disposed of in-water (ocean disposal or in the flow lane adjacent to the channel), along shorelines, or on upland sites. The volumes of material dredged annually do not reflect the rate of sedimentation in the river since most of disposal methods result in re-handling of material, and since a period of riverbed adjustment will follow each channel development action. Annual maintenance dredging since completion of the 40 x 600 ft channel (after 1976) has averaged 3.5 M cu.yd. per year in the estuary region (RM 4-50) plus 5.3 M cu.yd. per year in the Columbia River mouth (RM 0-4).

Figure 8. Annual volume (million cu. yd.) of dredged material handled during the development of and maintenance of the Columbia River navigation channel in the Columbia River estuary (Rm 4 to 50), 1900 to 1996. Data provided by U.S. Army Corp. (Portland, OR).



How did the construction of the navigation channel affect the estuary and its associated ecosystems? Basically, the navigation channel has concentrated flow in one deeper main channel, with several linked physical effects:

- reduced flow to side-channels and peripheral bays,
- reduced total surface area and volume of the estuary (tidal prism reduced 15%),
- reduced saltwater intrusion from its historical range and salinity throughout the estuary,
- reduced tidal currents relative to past (for comparable tidal ranges),
- altered the balance of circulation between the northern and southern channels,
- increased stratification of water column and reduced mixing,
- increased shoaling rates in the intermediate zone and peripheral flats, and
- altered habitat types.

The latter, for example, includes the disposal of dredge material and creation of barren land or islands. These habitats have increased availability for certain avian species and, thereby, contributed to increased predation on esutarine fishes, including salmonids (program currently underway, see Collis et al. 2000, Roby et al. 1998). Furthermore, when combined with regulated river flows, flushing time of particles or organisms in the estuary will increase relative to the past, due to reduced tidal exchange and river flows. Flushing time will also be less variable seasonally, but likely more variable spatially. Concentrated tidal and river flows in the main channels will reduce flushing from the peripheral channels and allow for increased deposition of fine sediments in those areas. These physical processes associated with the navigation channel, plus the changes in estuary habitats and regulation of river flows, provide strong inference that the turbidity maximum and biological production are likely to have decreased substantially over time. Unfortunately, the magnitude of change can not be assessed because no information exists on physical and biological processes before development. For the estuary in its current configuration, however, Simenstad et al. (1990) clearly emphasized the biological importance associated with the turbidity maximum and the intermediate energy zone of the estuary:

> "Abstract – Consumption processes at several trophic levels tend to converge in the central (estuarine-mixing) region of the Columbia River estuary, where living and detrital food resources are entrained within the energy null of the turbidity maximum zone. Primary consumers in this region are generalists and omnivorous feeders, capable of exploiting both autotrophic and heterotrophic food web pathways. In the presence of higher standing stocks of their prey resources, feeding by secondary and tertiary consumers is also concentrated, or more effective, in the estuarine mixing region of the estuary. …"

Exotic Species

The introduction of exotic species has almost always proven harmful to native fish communities and ecosystems and has seldom been controlled (Courtenary and Robins 1989, Tyus and Saunders 2000). Unfortunately, we know very little about the impact of these exotic species until it becomes all too obvious. Of 30 fishes that became extinct in the United States during the 20th century, introduced fishes were implicated in 24 extinctions and were the only factor acknowledged in two (Miller et al. 1989). For the Columbia River estuary, Weitkamp (1994) summarised the presence of 16 exotic fish and four exotic invertebrates known to date. Since then, however, two invasive crab species have been noted on the Pacific coast, the Green crab, *Carcinus maenas,* and the Chinese Mitten crab, *Eriocheir sinensis*[6]. As in most other situations, little can be quantified concerning the effect of these introductions but both species are considered to be significant predators in estuarine environments.

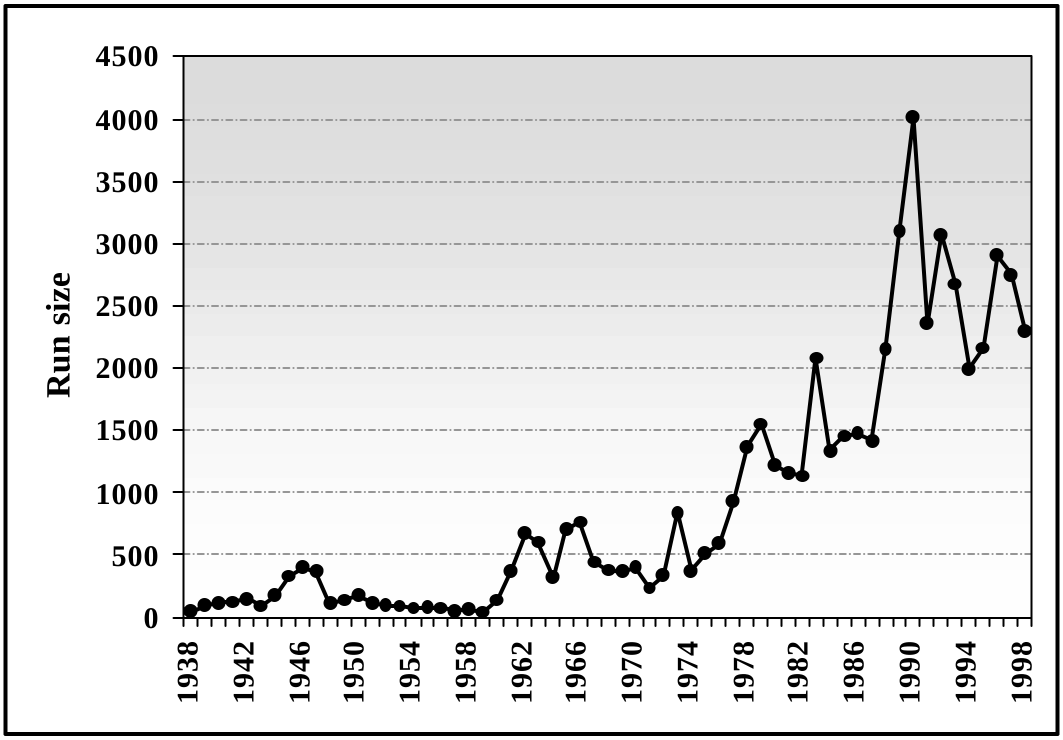
By far the most abundant exotic fish species is the American Shad, *Alosa sapidissima*. Shad were introduced to the Sacramento River in 1871 from the eastern seaboard, and

---

[6] for additional information on Green crabs see: http://www.wa.gov/wdfw/fish/shelfish/greencrab.htm and for Mitten crabs see: http://www.delta.dfg.ca.gov/mittencrab/life_hist.html

were observed in the Columbia estuary in 1876 (Craig and Hacker 1940). Harvest in the Columbia estuary began in 1888, but Craig and Hacker suggest that the early catch record was not indicative of abundance but “more nearly an index of the demand for or rate of disposal of the shad.” Recently, however, there is no doubt about their abundance (Figure 9); the only question centers on what their impact might be in the estuary. Shad juveniles (from age 0 to 2) are found in the estuary throughout the year (Bottom et al. 1984, Haertel and Osterberg 1967) and can be very abundant, emigrating from freshwater in their first fall at about 3-5 inches.

Figure 9. Minimum run size (x000 fish) of American Shad entering the Columbia River, 1938-1998 (WDFW & ODFW 1999). Run size does not include spawning populations below Bonneville Dam.



Water Quality and Pollutants

In an estuary that has relatively low industrial development and relatively high flushing rates, we may not expect water quality or accumulation of pollutants to be a major concern for the Columbia River. However, results of a recent study conducted by NMFS in several Pacific Northwest estuaries provides evidence for concern (NMFS NWFSC, Seattle, WA). Juvenile salmon collected from East Sand Island near the mouth of the Columbia River contained relatively high concentrations of DDTs and PCBs. These results raise questions about the source(s) of the contamination but have not yet been investigated.

Studies of sub-lethal exposure of juvenile salmon to contaminants in urban estuaries suggest that these contaminants could affect the survival, growth, and fitness of salmon (Casillas et al. 1996). A series of studies with laboratory and natural exposure of fall chinook salmon to aromatic and chlorinated hydrocarbons in Puget Sound estuaries demonstrate sub-lethal effects such as impaired growth, reduced immunocompetence, and increased susceptibility to diseases (Stein et al. 1995, Arkoosh et al. 1998a, Arkoosh et al. 1998b, Stehr et al. 2000). Furthermore, a recent study using the organophosphate insecticide, Diazinon, reported reduced antipredator and homing response in treated chinook salmon (Scholz et al. 2000).

Given the presence of these contaminants in some fishes collected in the Columbia estuary and sub-lethal effects that the contaminants may cause, the potential overall effect of this water quality issue could be reduced productivity in species that use the estuary for rearing, such as fall chinook and chum salmon. An in-depth report on water quality in the Columbia River estuary has been completed by the Lower Columbia River Estuary Program and can be accessed at: http://www.lcrep.org/home.htm

Hatchery Production of Salmonids

The production of hatchery fish in the Basin is clearly not a response to physical changes or loss of production in the estuary. The development of hatchery production through time, however, has proceeded assuming that capacity for survival and growth of hatchery fish would not be limited in the estuary or ocean (Brannon et al. 1999, Lichatowich 1999). Indirectly then, the expansion of hatchery production may limit production of naturally produced salmonids. The scale of hatchery production alone is a significant change in estuary use (Figure 10). Hatchery releases were summarized from the NRC (1995) database for the releases years 1950 through 1993. Data for release years 1994 through 1998 were summarized from agency records exchanged annually through the Pacific Salmon Commission. The latter data are maintained at the Pacific Biological Station, Nanaimo, BC (B. Riddell, pers. comm.). Releases of fall chinook salmon are also presented since under-yearling fall chinook migrants are known to use the estuary extensively for rearing.

Figure 10 indicates the scale of hatchery releases but is not very informative unless they can be related to historical production of naturally produced salmonids. Obviously any such estimation involves several assumptions, but rough estimates can be derived from peak historical catches by species, and applying reasonable (but conservative) values for terminal harvest and marine survival rates. For example, using historical catch data from Chapman (1986) and Craig and Hacker (1940), the following range of estimates for historical production of salmonid emigrants were derived (Table 4).

Figure 10. Total releases of salmonids (millions) in the Columbia River basin for release years 1950-1998, including releases of Fall chinook salmon. Releases of Fall chinook were only summarized for the period 1975-1998.

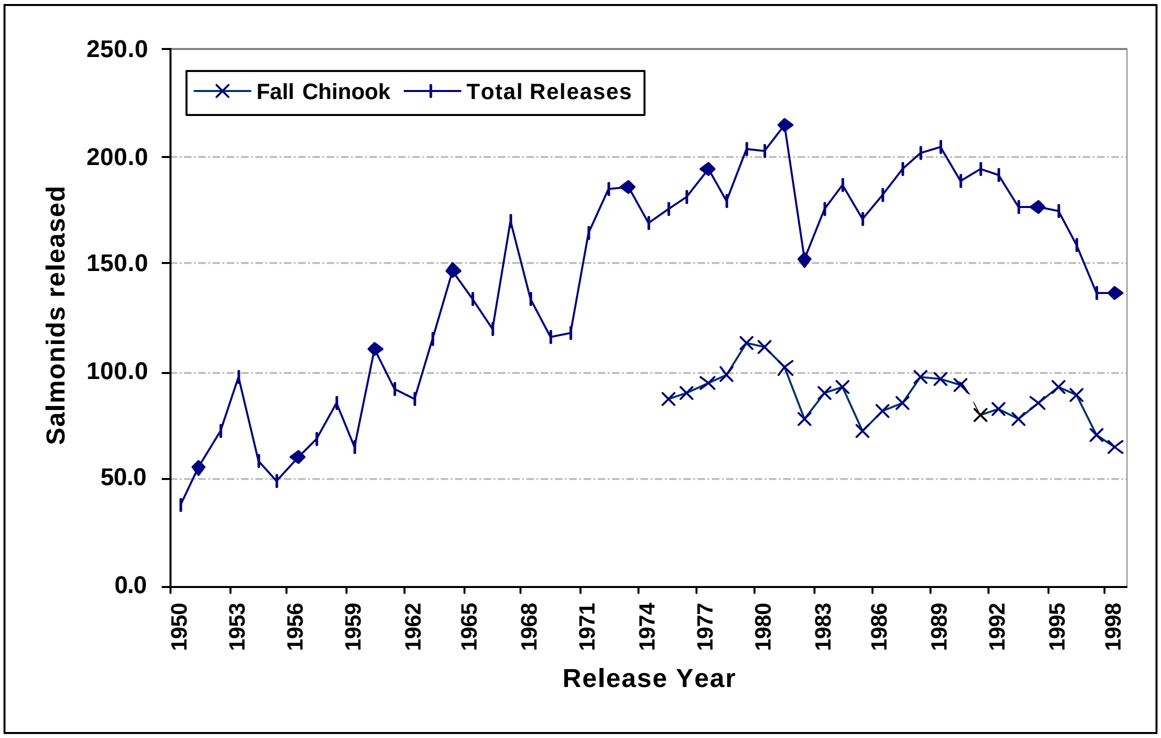


Table 4. Estimated numbers of naturally produced smolts emigrating from the Columbia River during peak catch periods, as identified by Chapman (1986)[7], numbers of smolts expressed in millions. Hatchery contributions during these periods would have been negligible to none.

Species	Historical Peak Catches	Terminal Harvest Rates	Marine survival rates, smolt to adult (%)			
			2.5%	5%	10%	15%
Sockeye	1,400,000	0.50		56,000	**28,000**	18,667
Summer chinook	1,400,000	0.70		**40,000**	20,000	13,333
Spring chinook	400,000	0.50		**16,000**	8,000	5,333
Fall chinook	1,100,000	0.40	110,000	**55,000**	27,500	
Coho	476,000	0.33		28,850	**14,425**	9,616
Chum	359,000	0.33	**43,515**	21,758	10,879	
Steelhead	382,000	0.25		30,560	15,280	**10,187**

---

[7] The historical peak catch for sockeye is less than in Chapman (1986). Chapman's value averaged each annual value but was strongly influenced by one year. The peak value in this table is calculated as one expansion estimated over the sum of the 5 years used by Chapman.

The bold values in the table are those values for each species that are most likely and total over 200 million smolts. Whether these levels of production could be supported within one year is not known. Overall, however, there are some notable changes (e.g., the loss of chum and summer chinook production), particularly since the vast majority of upper river spring and summer chinook, and lower river spring and fall chinook are now produced in hatcheries. It may also be notable that under the assumptions used, the hatchery production of fall chinook (Fig. 10) plus current natural production of Columbia River Bright fall chinook would equal or exceed the historical production of fall chinook smolts. Given the changes in estuary habitats, the survival and growth of these fall chinook in the present estuary should be a concern. Furthermore, the timing of emigration of hatchery fish through the estuary is much more compressed in duration and season than in the past.

We should also note, however, that all the salmonids released in the Columbia River basin above Bonneville Dam will not reach the estuary. In recent years, the Fish Ecology Division, NWFSC NMFS has calculated the annual "percentages of listed wild and hatchery fish at selected Columbia and Snake River projects" (provided by Protected Resources Division, NOAA NMFS, Portland, OR 97232). For example, the total release of hatchery fall chinook in 1998 was reported to be 64.2 million (for all agencies in the Columbia Basin); but the estimated number of hatchery plus wild fall chinook expected to reach the Columbia estuary (to Tongue Point, under a full transportation with spill scenario) was only 61 million subyearling smolts (Feb. 11, 1998 NMFS memorandum, F/WNC3 – M. Schiewe).

Changes relative to the Fish and Wildlife Program

Before human influence, the Columbia River estuary would have been a high-energy environment dominated by physical forces, with extensive sand-beds and highly variable river flows. Several authors have suggested that the biological processes in this environment may have been unique on the Pacific coast. The estuary of today, however, has been extensively modified in terms of physical processes and is substantially less variable than in the past. The effects of these changes on fish and wildlife would be mediated through changes to biological processes within the estuarine ecosystem and depend on the susceptibility of a species to these changes.

Seamen (1977) provided the first comprehensive inventory of the fish and wildlife inhabiting these estuarine habitats. Wildlife extensively use the estuary, but a linkage of change in wildlife use or abundance with hydrosystem development and operation is not obvious. There are possible exceptions though, such as reduced peripheral wetland habitats due to flood suppression, increased availability of haul-outs for marine mammals, or increased abundance of marine birds (see Collis et al. 2000, Roby et al. 1998). The effects of greatest relevance, however, involve the use of estuary by fishes and changes to their ecosystem.

The fish communities of the Columbia River estuary are similar to other Pacific northwest estuaries (Haertel and Osterberg 1967, Bottom et al. 1984, Bottom and Jones

1990). Changes in communities (species composition) were associated with salinity gradients and seasons, and the distribution of fish abundance was strongly influenced by prey density. Bottom and Jones (1990) provide an excellent example of how the physical processes described previously are interrelated with biological processes and fish production.

> "We speculate that river discharge, circulation energy, and sedimentation processes that influence the retention of organic materials and the maintenance of zooplankton populations within the Columbia may ultimately control the feeding environment and production potential of the estuary for fish." (pg. 266)

Seasonal changes in communities were related to life history stages of the marine and anadromous fishes. The abundance of salmonids was greatest during the spring and early summer, and their use of the estuary was similar to that of species in other estuaries (Healey 1982, Simenstad et al. 1982)[8]. In general, species or life history types with large smolts (coho, steelhead, and yearling chinook) tend to use the outer portions of estuaries (deeper water habitats) and have a short residence period. Smaller smolts (sub-yearling chinook, chum, or early migrants) utilize the estuary for extended periods (a few to several weeks) and may comprise a large portion of the fish community. As these fish grow, they move offshore from the shallower more protected environments to deeper water channels. Sub-yearling chinook and chum salmon show the most extensive use of estuaries. Healey (1982) describes the use of tidal creeks, sloughs, and marsh habitats in the upper estuary by chum and chinook fry. On high tides, fry feed along the tidal fringe and on low tides retreat into tidal creeks or channels for shelter. As these fry grow through the season, they move seaward to the outer estuary. Observations on emigration timing and estuary use in the Columbia estuary are consistent with these observations (coho salmon, Durkin 1982; sub-yearling chinook, McCabe et al. 1986; and salmonids, Dawley et al. 1986). These papers add two additional observations: larger smolts tend to emigrate first, and smolts migrating from further upstream tend to move through the estuary more quickly. Little seems to be known about the use of the Columbia estuary by chum or sockeye salmon, or cutthroat trout (likely due to their infrequent recoveries).

Because of extended rearing in the estuary, fry and sub-yearling chinook, chum salmon, and smaller coho salmon are the most likely salmonids or life history stages to be affected by the potential effects of changes in the estuary. Just in terms of the physical features, Healey (1982) suggested that the complexity of estuarine habitats "all contribute to the carrying capacity for young salmon, and that the appropriate configurations must be conserved if salmon production is to be maintained." This has certainly not been the case in the Columbia River estuary.

If this is not the case, then what biological processes have been affected? The most notable effects have likely been on the estuarine food web. Most food webs (the linkage between consumers and their food resources) in Pacific northwest estuaries are based on

---

[8] Description of the estuary use by pink salmon differ between these authors but pink salmon are not of concern in the Columbia River estuary. Healey reports that Fraser River sockeye salmon have limited use of their estuary but little is known about sockeye use of the Columbia River estuary.

detritus (organic debris from decomposing plants or animals), but the composition of the organic matter varies among different estuaries, and its value as a food source may vary (Simenstad 1997). Sources of detritus may include emergent plants in peripheral wetlands (macrodetritus), benthic algae, plankton produced in estuarine waters, and fluvial inputs of plankton from up-river sources when mixed with estuarine sources. Given the loss of peripheral wetlands (Thomas 1983), increase in water storage in the hydrosystem, and reduced flooding and flow variation, the recruitment of macodetritus from within the estuary has been substantially reduced from the pre-development period (Sherwood et al. 1990). Development of the upper river has, however, resulted in an increased influx of freshwater phytoplankton that lyse when mixed with estuarine waters, producing microdetritus. For the estuary that was sampled during the early 1980s, Simenstad et al. (1990) concluded “that suspended detrital particles, originating principally from upriver but also produced within the estuary at the freshwater-brackishwater interface and washed in from peripheral marshes, essentially supported the estuarine food web.”

The relative value or productivity of the endogenous macrodetritus-based food web compared to the current exogenous microdetritus-based web is uncertain. Some authors suggest that the microdetritus-based system has lower energetic value, but also that the material is more labile than larger organic particles from macrodetritus. Simenstad (1997) has also suggested that the quality of the organic matter is fundamentally more important than the “bulk” of the matter, and that the supply of detritus varies by season and proximity to habitats. The availability of food sources or prey to a species of interest may be an equally important question. The macrodetritus-based system likely involved greater diversity of feeding habitats and prey in peripheral wetlands and tidal flats, that subsequently contributed to communities in the estuary mixing zone. The microdetritus-based system is closely associated with suspension feeding zooplankton and the turbidity maximum zone (located in the water column of the estuary’s central mixing zone). Subyearling chinook and chum salmon, for example, are not likely to benefit from prey production in the central estuary when their rearing habitats are peripheral flats and marshes.

The availability of prey introduces two other biological processes: competition and predation. Fishes in the Columbia River estuary consume a wide variety of prey, but the bulk of the food is usually comprised of only a few species, and the distribution of fish is strongly influenced by prey availability (Haertel and Osterberg 1967, Bottom et al. 1984, Bottom and Jones 1990). Among species, McCabe et al. (1983) reported substantial diet overlap comparing salmonid and non-salmonid fishes, particularly between sub-yearling chinook and American shad, threespine sticklebacks, and starry flounder. These three species are numerically abundant in the estuary. The only evidence for density dependent interactions that may limit growth and survival of salmonids, however, has been presented by Bottom et al. (1984), and subsequently in Bottom and Jones (1990). Mean feeding intensity for sub-yearling chinook in the Columbia estuary was lower than reported for a few other estuaries. Bottom et al. (1984) expressed caution in comparing feeding intensity between surveys, and their data for feeding intensity were only based on one year of data, 1980. In Bottom and Jones (1990), though, these data were compared to three other studies that consistently indicated higher levels of feeding intensity in other estuaries (two studies in Oregon, one in British Columbia). Bottom and Jones (1990) state that “these observations (and the apparent relationship between stomach fullness and densities of potential prey) cause us to question whether fish consumption and production in the Columbia may be limited by availability of prey or the feeding efficiencies of predators in a highly turbid and dynamic environment.”[9] Obviously, no conclusions should be drawn from a single year of sampling that was conducted under unusually high turbidity conditions, but these results and the numbers of hatchery fish being introduced to the system certainly generate concern about the potential for density dependent limitations. There does not appear to be any information concerning interactions of sub-yearling chinook and chum salmon, presumably reflecting the few chum collected during these studies (Bottom et al. 1984). Furthermore, during this study period, predation on juvenile salmonids by non-salmonids and other juvenile salmonids was insignificant (McCabe et al. 1983). In other estuaries, however, inter-specific predation between salmonids is known (Simenstad et al. 1982), and many marine fishes are known to prey on salmonids.

The potential interaction of hatchery reared salmonids with naturally reared salmonids could involve intra-specific competition and/or inter-specific competition and predation (Myers and Horton 1982, Simenstad et al. 1982). Based on observations to-date and specifically within the Columbia estuary, however, the rapid movement of larger smolts through the estuary apparently minimises these interactions (although detailed investigations of these concerns do not seem to have been conducted). A potential indirect interaction though, may be the role of hatchery production in stimulating predator responses to a consistent annual supply of food delivered through a narrow “time window” in the estuary. Natural populations are inherently more variable in size, timing, use of habitats, etc. These natural variations may indirectly play an important role in spreading predation risk on natural populations.

In the Columbia River estuary, the largest known source of predation is due to marine birds. Studies currently being conducted have demonstrated extensive predation on migrant salmonids and have provided the first quantitative estimates of these losses. Collis et al. (2000) estimated that during 1998, five species of marine birds consumed 16.7 million smolts (range 10.0-28.3 million) or 18% (range 11-30%) of the smolts that reached the estuary. Caspian terns alone accounted for 65% of the mortality. The largest known Caspian tern (*Sterna caspia*) breeding colony in North America (about 8,000 breeding pairs in 1998) existed on Rice Island, a dredge disposal site, in the upper Columbia River estuary (Collis et al 2000). Studies of diet composition have demonstrated that terns at the Rice Island colony are highly dependent on salmonids (75% of diet composition by mass in 1997 and 1998), and that terns in the lower estuary are much less dependent upon salmonids. This reduced dependence in the lower estuary presumably reflects the greater diversity of marine fishes for prey in that region. Other avian predators were similarly much less dependent on salmonids when nesting in the lower estuary.

---

[9] Recall that the eruption of Mount St. Helens on May 18, 1980 greatly increased the turbidity of the estuary during this study period.

Emmett (1996) has also identified the predation on juvenile and adult salmonids by marine mammals. Evidence for predation as a limiting factor to salmonid production in the Columbia River seems to be limited to the presence of wounds on adults (Fryer 1998), diet composition studies (Browne et al. 1999, Laake et al. 1999) and the increasing population size of Harbour seals in the estuary. Harbour seals are generalist feeders and differences in frequency and number of prey probably reflect the temporal availability and abundance of prey rather than selection by the predator. However, in some estuaries predation on adult salmon can be substantial (Brown and Mate 1983, Bigg et al. 1990, Olesiuk et al. 1996). These estuaries though tend to be smaller with less turbidity and frequently involve some condition that aggregates the salmon so that their vulnerability increases. The channelization of the Columbia River estuary suggests such a condition but the area involved is still very large and the turbidity high. Consequently, the impact of marine mammal predation on salmonids remains uncertain.

1994 Fish and Wildlife Program

The Council's interest in this topic has been well founded given the extent of physical and biological change documented in the Columbia River estuary. Effects of change in this estuary operate through a highly energetic, integrated physical environment. Biological processes are closely linked to changes in circulation, salinity intrusion, and sedimentation. The development and operation of the hydroelectric system have contributed significantly to these changes. Direct effects occur through changes in seasonal flow rates, reduced sediment discharge, and resultant changes in the estuary's energy balance. Indirect effects occur because of changes to freshwater ecosystems, establishment of introduced species, and the enormous investment in hatchery production of salmonids to mitigate for related losses. So how has the Council's Fish and Wildlife Program (NWPPC 1994) addressed these changes and impacts?

The ISAB has been aware of concerns that the Program did not adequately address the importance of the estuary to fish and wildlife. The Program does make only limited reference to wildlife and the estuary, and each reference pertain to the impact of predators on salmonids (Secton 5.7). On the other hand, the Program does specifically address the prevailing hypotheses about how estuarine environments influence the production of salmonids. They serve as a "window of opportunity" to optimize survival due to a temporal coherence of factors, or act as a "bottleneck" that limits the carrying capacity of the estuarine environment (see Simenstad 1997).

The Program's section 5 on juvenile salmon migration acknowledges that the overall survival of fish is the cumulative effect of many life stages and environments.

> "The relationship between actions taken in the river and overall fish survival is not simple. Survival from the smolt stage to adult spawner is the result of a host of factors, only a few of which are under human control. Important relationships can be obscured because improved survival at one life stage can be negated by changes in survival at other life stages. Some survival conditions in the ocean, for example, can vary independently of survival conditions in the river or estuary." page 5-8 (NWPPC 1994)

The mechanism affecting survival in this section though, involves both the timing of arrival of smolts to the estuary and a "physiological window" to enhance survival.

> "d. At the estuarine stage, flow/water velocity could influence survival through its effect on migration speed and fish condition. This in turn can affect the date of entry into the estuary to coincide with food availability or predator concentrations and/or by influencing the arrival to the estuary within a physiological window that enhances the likelihood of a successful salt water transition." page 5-11 (NWPPC 1994)

Section 7.2D also strongly implies a "window of opportunity" concept for the estuary. In referring to the need to improve hatchery propagation, the Program states that "downstream migration must be programmed to coincide with the most favorable conditions of food availability, …" (page 7-16). The term "programmed" refers to matching release time to changes in river and estuary conditions.

The principle reference to the estuary occurs in Section 7, Salmon Production and Habitat. Section 7.1 addresses evaluation of carrying capacity for salmon in Columbia basin environments. In particular, Section 7.1.A essentially encompasses all aspects of investigation, management, and monitoring to evaluate "salmon survival, ecology, carrying capacity, and limiting factors" in all Columbia basin environments, i.e. "… of tributary, mainstem (including reservoirs), estuary, plume, and near-shore ocean". This section also relates back to the "window of opportunity" concept by calling for a monitoring program "to identify optimal timing for residency in the estuary and the near-shore environment". The Program subsequently (Section 7.1G) calls for adjusting the total number of hatchery fish released to stay within the Basin carrying capacity, noting that the capacity of the Basin to support young fish has decreased during this time (reference to the late 1800s).

Because the next amendment of the Fish and Wildlife Program is currently in review (NWPPC 2000), we will not undertake detailed comments on these specific measures in the 1994 Program. With respect to the estuary, we definitely support the ecosystem approach of the 2000 Program, but are concerned about the possible inclusion of specific measures as expressed above. The objectives that an "optimal" window for salmon survival can be determined, and that hatchery production can be "programmed" to coincide with the "most favorable" estuary conditions are likely not achievable. They perpetuate a technical or engineered attitude that there exist a single optimal period for survival and that we can understand the complex of cues that salmon utilize in their migration timing. That attitude does not seem to acknowledge the degree of uncertainty that must exist in the highly modified river-estuary linkage or the importance of diversity in coping with this modified environment. The idea of a carrying capacity, as a fixed level of fish production that can be sustained, tends to simplify production potential into single species and/or single environment issues, ignores the potential interaction between environments, and minimizes the inherent annual variability in these production processes. Furthermore, establishing the carrying capacity of altered habitats in the Columbia basin may identify limiting factors in certain environments but is not likely to be informative about potential production levels or processes. A conclusion by Simenstad (1997) clearly supports the shift from specific measures to the more general ecosystem-based Program objectives:

> "Ultimately, we must recognize that increased knowledge about the influence of dynamic ecosystems such as estuaries on salmon is more likely to elucidate the constraints upon alternative salmon management strategies rather than predictable relationships that can be used to "take advantage" of estuaries."

Discussion

The ISAB was asked to review the impacts of estuarine conditions on the Council's mission to "protect, mitigate and enhance" fish and wildlife in the Columbia River as affected by development and operation of the hydroelectric system. The intent of this report has been to provide a summary of more technical documents (see Seaman 1977, Simenstad et al. 1984, Small 1990, Thomas 1983) and to relate changes in the estuary to the Fish and Wildlife Program. Those technical documents provided excellent background materials on physical aspects of the estuary, and drew extensively on the 1980-81 biological data collected by the Columbia River Estuary Data Development Program. Our ability to assess impacts of estuarine conditions on objectives of the Program, however, has been limited by a lack of appropriate and available data[10]. Information necessary to meet the 1994 Program objectives described in the previous section has simply not been acquired for the estuary. Similar obstacles were expressed to the ISAB by the NMFS study team who noted that the data are insufficient to even determine the extent of modern estuarine use (reference to salmonids).

While data limitations prohibit us from concluding what impacts that altered estuarine conditions have had on the Council's mission, we can comment on components of the question, such as:

1) How have estuarine conditions changed through time?
2) Is there evidence for potential impact of these changes on objectives of the Council's Program? and
3) What actions in the estuary might be anticipated to be consistent with the proposed new Program?

Clearly there is extensive documentation about changes in the estuary over the past century, the major changes resulting from development of peripheral wetlands and their isolation from the estuary, development and deepening of the Federal Navigation Channel, and regulation of upper Columbia River flows for hydrosystem needs and flood control. The effects of these changes do not function discretely. The estuary is a complex interaction of physical features (predominated by the energy balance between river flow and tidal forces), resultant changes in circulation, salinity intrusion, and sediment processes, and ultimately the biological consequences of these changes. Superimposed on this dynamic environment have been changes in water quality,

---

[10] These comments do not pertain to surveys or data on water quality since we have not examined that type of information.

introduction of exotic species, and major increases in the production of hatchery reared salmonids.

The question of the potential biological impacts associated with these changes is more complicated than detecting the physical impacts. Changes in the biological processes varied from a fundamental alteration in the basis of the food web to the exclusion of sub-yearling chinook and chum salmon from a large portion of the tidal marshes. The effects of these specific changes, however, are difficult to partition from the effects of numerous other impacts in the Basin. For example, one might ask whether the reduction of estuary habitat caused the decline in Columbia River chum salmon or has it been a minor component of a species in decline at the southern range of its natural distribution? Or, have the changes been detrimental to one species but beneficial to others? Given the magnitude of the Columbia basin and the number of species involved, there are of course a myriad of questions such as these. If, however, we focus only on salmonids, it is the ISAB's assessment that the impact of change in the estuary has been detrimental to salmonids and the rebuilding objectives of the Fish and Wildlife Program.

We base this advice principally on three major issues:
1. The significant loss of peripheral wetlands and tidal channels; these habitats are important to the early rearing, survival and growth of chum salmon, sub-yearling chinook, and smaller coho salmon in other west coast estuaries.
2. The extent of change to seasonal flows following development of the hydrosystem. The affects of these changes are closely associated with the impact of the development of the navigation channel. In combination these developments have resulted in changes to estuarine circulation, deposition of sediments, and biological processes.
3. The need for precautionary advice given the current state of most salmonid populations in the Basin, the magnitude of change in the estuary, and the lack of investigations upon which to base alternative advice.

Investigators working in the estuary are to be complimented for their quality of work and use of the limited biological data available. The use of historical bathymetric charts, combined with tidal data, and numerical modelling have provided significant insight into the energetics of the estuary, changes in circulation, definition of habitat zones in the estuary and lower river. Biological data, however, has not been collected at appropriate temporal and spatial scales. Biological relationships follow very few physical rules; their responses to stochastic events are unpredictable and the outcome in the life cycle of an individual result from the cumulative effects over numerous habitats and time periods. Consequently, to understand the importance of the estuary in determining specific life histories or in controlling production from a population will require vastly greater investment in research than has occurred. As a result, we can not at this time provide adequate responses for the Council on how the estuary has affected objectives of the Fish and Wildlife Program. Given the specific measures identified in the 1994 Fish and Wildlife Program, expenditures for appropriate and necessary estuarine studies have simply not been adequate.

Because this work on biological relationships has not been conducted, it does generate the question whether the detailed studies should now be undertaken, whether they are consistent with the goals of the 2000 Fish and Wildlife Program, and how the research should be conducted? We also note that the 2000 Fish and Wildlife Program calls for the establishment of monitoring and evaluation programs to isolate freshwater and marine sources of mortality. The inclusion of the estuary as a province in the freshwater life phase could compromise the ability to separate freshwater and marine mortality. For example, it is important to consider how the number of salmonids entering the ocean plume environment will be estimated, or how to delimit survival in freshwater and marine phases of the life cycle?

Some detailed basic biological studies will be necessary just to design appropriate monitoring and evaluation programs. To reduce the likelihood of prolonged uncertainty about the impact of estuarine conditions, however, the ISAB recommends an aggressive experimental program targeted to study known changes to the estuary. That program should incorporate monitoring of the physical environment (such as currently begun via the CORIE program, Oregon Graduate Institute) combined with evaluation of large-scale manipulations of estuarine habitats. The intent of these programs would be to address changes that are presumed to have had negative impacts and to conduct studies at a scale that can be measured within the natural environment. These types of programs would be consistent with the vision statement in the 2000 Fish and Wildlife Program:

> "Wherever feasible, this program will be accomplished by protecting and restoring the natural ecological functions, habitats, and biological diversity of the Columbia River Basin."

The types of large-scale programs that are envisioned include:

a) removal of dykes in the lower river and upper estuary to restore connections between peripheral floodplains and the river or fluvial zone of the estuary. Clearly such a program would depend on the use and ownership of these old floodplains but there are likely areas that are no longer in use for agriculture and/or the use may benefit from periodic inundation by the river and its sediments. Productivity of flooded versus dyked peripheral plains and use of flooded plains should be monitored.

b) actively manage sources of salmonid predation in the estuary through restoration of natural habitats, removal of habitats artificially created due to channel construction and/or maintenance, or controlling predator populations. For example, Rice Island was created from dredge material and in recent years has supported the largest Caspian Tern colony in North America. Research has demonstrated the substantial predation impact of these birds on salmonids (Collis et al. 2000, Roby et al. 1998). Management of this colony could have immediate benefits for conserving salmon migrants and have beneficial effects on the long-term viability of the Caspian Tern in this region. Historically, Caspian Terns nested in numerous small colonies but have more recently shifted to fewer and larger colonies on human-created habitats along the Pacific coast (Gill and Mewaldt 1983). However, fewer and larger colonies increase the risk to the species through catastrophic events, possibly via disease, predators, or an environmental event.

Restoring the natural population structure of this species could reduce the risk of loss and improve its productivity, and reduce salmonids losses.

c) establish an allocation of water within the annual water budget for the Basin, that would simulate peak seasonal discharge, increase the variability of flows during periods of salmonid emigration, and restore tidal channel complexity in the estuary (aided by removing pile dykes where feasible). The reduction in peak seasonal discharge under the current hydrosystem is one of the most significant changes in river-estuary system. Short duration pulses of controlled but higher flows would be intended to increase turbidity to reduce predation, increase movement through the estuary, increase sediment transport into the estuary, and connect the river system with restored floodplain habitats.

Initially, we anticipate that people will think that such programs are unnecessary and/or impractical. To achieve the vision statement of the 2000 Fish and Wildlife Program in the estuary province, however, programs of these magnitudes are likely necessary given the magnitude of the environment and the stated desire to evaluate these actions. Large programs though do have their logistic and management concerns. In the estuary, for example, is there an appropriate organization to identify and prompt ecosystem studies, develop experimental procedures, and evaluate and report results? Such programs are inherently costly and require a commitment of resources for several years; how can these resources be provided and protected over time?

The ISAB also notes that while these logistic and management concerns were identified pertaining to the estuary, we expect that under the broader ecosystem objectives of the 2000 Fish and Wildlife Program that similar concerns will develop throughout the Basin.

Finally, in the lower Columbia River and estuary, the interests of the Council seem consistent with the interests of the Lower Columbia River Estuary Program (LCREP 1999), developed as part of the National Estuary Program. Clearly, the development of any major program or institutional arrangement in the estuary province should consider their work and objectives.

Acknowledgements

The ISAB wishes to acknowledge and thank organizations and individuals that assisted during this review. The Columbia River Estuary Study Team (CREST, Astoria, OR) provided a number of important documents and maps. The U.S. Army Corp. (Portland, OR) provided historical data on annual dredging volumes. Dr. D. Jay and N. Paik (Oregon Graduate Institute) freely provided data on stream flows and sediment volumes, and provide advice on numerous inquiries. Dr. M. Schiewe, J.E. Stein and E. Casillas (NMFS, Seattle, WA) and R.A. Koch (NMFS, Portland, OR) provided useful literature citations, reprints, and memos concerning several topics in the review. Dr. D. Roby (Oregon State Univ., Corvallis, OR) and K. Collis (RTR Consultants, Bend, OR) provided unpublished materials concerning avian predation in the Columbia River estuary and useful advice. Ms. Kay Dewar (Civil and Environ. Engineering, Univ. Washington, Seattle, WA) kindly produced the map used in this text. Mr. David Liberty and the StreamNet Library (Portland, OR) provided invaluable service in finding reference materials. Finally, staff of the Point Adams Station (Hammond, OR) and NMFS provided an invaluable site visit to the Columbia River estuary. The assistance of all has been greatly appreciated.

Literature Cited

Arkoosh, M.R., E. Casillas, P. Huffman, E. Clemons, J. Evered, J.E. Stein, and U. Varanasi. 1998a. Increased susceptibility of juvenile chinook salmon from a contaminated estuary to Vibrio anguillarum. Trans. Am. Fish. Soc. 127:360-374.

Arkoosh, M.R., E. Casillas, E. Clemons, A.N. Kagley, R. Olson, P. Reno, and J.E. Stein. 1998b. Effect of pollution on fish diseases: potential impacts on salmonid populations. J. Aquat. An. Health 10:182-190.

Bigg, M.A., G.M. Ellis, P. Cottrell, and L. Milette. 1990. Predation by harbour seals and sea lions on adult salmon in Comox harbour and Cowichan Bay, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 1769: 31p.

Bottom, D.L. and K.K. Jones. 1990. Species composition, distribution, and invertebrate prey of fish assemblages in the Columbia River estuary. Progress in Oceanography 25: 243- 270.

Bottom, D.L., K.K. Jones, and M.L. Herring. 1984. Fishes of the Columbia River estuary. Columbia River Data Development Program, 113 p. CREST, 750 Commercial St. Rm. 205, Astoria, OR 97103.

Brannon, E.L., Currens, K.P., Goodman, D.,Lichatowich, J.A., McConnaha, W.E., Riddell, B.E., and R.N. Williams. 1999. Review of artificial production of anadromous and resident fish in the Columbia River, Part I: A Scientific basis for Columbia River production program. Northwest Power Planning Council, Portland, OR. 139p.

Brown, R.F. and B.R. Mate. 1983. Abundance, movements, and feeding habits of Harbor seals, Phoca vitulina, at Netarts and Tillamook Bays, Oregon. Fishery Bulletin 81(2): 291-301.

Browne, P, J.L. Laake, and R.L. DeLong. 1999. Diet of harbor seals (Phoca vitulina) in the Columbia River I: Composition of prey taxa indentified from multiple structures. In: Pinniped predation on salmonids: Preliminary reports on field investigations in Washington, Oregon, and California. provided by NMFS, Northwest Region, Seattle, WA.

Buchanan, K. 1977. Columbia River Estuary Fishes. Section 306 ***in*** Seaman, M.H. et al. 1977. Columbia River Estuary Inventory of Physical, Biological, and Cultural Characteristics. prepared for the Columbia River Estuary Study Taskforce (CREST), 750 Commercial St. Rm. 205, Astoria, OR 97103.

Casillas, E., B.B. McCain, M. Arkoosh, and J.E. Stein. 1996. Estuarine pollution and juvenile salmon health: potential impact on survival. pp. 169-178. In Estuarine and Ocean Survival of northeastern Pacific Salmon. NOAA Tech. Memo. NMFS-NWFSC-29.

Collis, K., S. Adamany, D.D. Roby, D.P. Craig, and D.E. Lyons. 2000. Avian predation on juvenile salmonids in the lower Columbia river. 1998 Annual report to Bonneville Power Administration, Portland, OR, Contract No. 97BI33475, Project No. 97-024-00, 101 p. (BPA Report DOE/BP-33475-2)

Columbia River Estuary Data Development Program (CREDDP). 1980. Volume 1 Summary plus maps. Volume II Annotated Bibliography. Pacific Northwest River Basins Commission, Vancouver, WA. (CREST, 750 Commercial St. Rm. 205, Astoria, OR 97103).

Costello, R.J. 1996. A literature review, bibliographic listing, an organization of selected references relative to Pacific Salmon and abiotic and biotic attributes of the Columbia River estuary and adjacent marine and river environs for various historical periods: Measure 7.1A of the Northwest Power Planning Council's 1994 Fish and Wildlife Program. Final report. Bonneville Power Administration, PO Box 3621, Portland, OR 97208-3621. DOE/BP-62611-9 September 1996 7C (20 p. plus appendices).

Courtenay, W.R. Jr., and C.R. Robins. 1989. Fish introductions: good management, mismanagement, or no management. Rev. Aqua. Sci. I: 159-172.

Chapman, D.W. 1986. Salmon and steelhead abundance in the Columbia River in the nineteenth century. Trans. Amer. Fish. Soc. 115: 662-670.

Craig, J.H. and R.L. Hacker. 1940. The history and development of the fisheries of the Columbia River. U.S. Bur. Fish., Bull. 49: 133-216.

Dawley, E.M., R.D. Ledgerwood, T.H. Blahm, C.W. Sims, J.T. Durkin, R.A. Kirn, A.E. Rankis, G.E. Moran, and F.J. Ossiander. 1986. Migrational characteristics, biological observations, and relative survival of juvenile salmonids entering the Columbia River estuary, 1966-1983. Final report to Bonneville Power Administration, U.S. Dep. Energy, Contract DE-A179-84BP-39652, 256p.

Durkin, J.T. 1982. Migration characteristics of coho salmon (Oncorhynchus kisutch) smolts in the Columbia River and its estuary. p. 365-376. In V.S. Kennedy (Ed.). Estuarine Comparisons. Academic Press, NY.

Emmett, R.L. 1997. Estuarine survival of salmonids: The importance of interspecific and intraspecific predation and competition. pp. 147-158. . *In* Emmett, R.L. and M.H. Schiewe. Estuarine and Ocean Survival of Northeastern Pacific Salmon. NOAA Tech. Memorandum NMFS-NWFSC-29.

Fryer, J.K. 1998. Frequency of pinniped-caused scars and wounds onn adult spring-summer chinook and sockeye salmon returning to the Columbia River. N. Amer. Journ. Fish. Manag. 18:46-51.

Fulton, L.A. 1970. Spawning areas and abundance of steelhead trout and coho, sockeye, and chum salmon in the Columbia River basin – Past and Present. NOAA/NMFS Special Scientific Report No. 618. 37p.

Gill, R. E. and L.R. Mewaldt. 1983. Pacific coast Caspian terns: Dynamics of an expanding population. The Auk 100: 369-381.

Graves, J.K., J.A. Christy, P.J. Clinton, and P.L. Britz. 1995. Historic Habitats of the Lower Columbia River. 14p. plus map. (CREST, 750 Commercial St. Rm. 205, Astoria, OR 97103).

Healey, M.C. 1982. Juvenile Pacific salmon in estuaries: The life support system. pp. 315-341. *In* V.S. Kennedy. Estuarine Comparisons. Academic Press.

Jay, D. and J.D. Smith. 1990. Circulation, density distribution and neap-spring transitions in the Columbia River estuary. Prog. Oceanog. 25: 81-112.

Jay, D.A., B.S. Giese, and C.R. Sherwood. 1990. Energetics and sedimentary processes in the Columbia River estuary. Prog. Oceanog. 25: 157-174.

LCREP. 1999. Comprehensive Conservation and Management Plan. Volume 1. Comprehensive conservation and management plan. Lower Columbia River Estuary Program, 811 SW Sixth Ave., Portland, OR 97204

Laake, J., P. Browne, R. DeLong, and H. Huber. 1999. Diet of harbor seals (Phoca vitulina) in the Columbia River II: Consumption of salmonids and other prey. In: Pinniped predation on salmonids: Preliminary reports on field investigations in Washington, Oregon, and California. provided by NMFS, Northwest Region, Seattle, WA.

Lauff, G.H. (Ed.). 1967. Estuaries. American Association for the Advancement of Science. Publ. 83. Wash. D.C.

Lichatowich, J. A. 1999. Salmon without rivers: a history of the Pacific salmon crisis. Island Press, Wash. D.C. 317p.

McCabe, G.T. Jr., W.D. Muir, R.L. Emmett, and J.T. Durkin. 1983. Interrelationships between juvenile salmonids and nonsalmonids in the Columbia River estuary. Fishery Bulletin 81(4): 815-825.

McCabe, G.T. Jr., R.L. Emmett, W.D. Muir, and T.H. Blahm 1986. Utilization of the Columbia River estuary by subyearling chinook salmon. Northwest Science 60(2): 113-124.

Miller, R.R., J.D. Williams, and J.E. Williams. 1989. Extinctions of North American fishes during the past century. Fisheries 14(6):22-38.

Morgan, J.B. et al. 1979. An annotated bibliography of the Columbia River Estuary. Oregon Estuarine Research Council, Sea Grant Publication No. ORESU-L-79-002, Oregon State University, Corvallis, OR. 99 pp. (4 sections).

Myers, K.W. and H.F. Horton. 1982. Temporal use of an Oregon estuary by hatchery and wild juvenile salmon. pp. 377-392. In V.S. Kennedy. Estuarine Comparisons. Academic Press.

NMFS Northwest Fisheries Science Center. 2000. Preliminary data on contaminant concentrations in salmonids and prey from the Columbia River estaury. EC Division. Interim Rept., Sept. 2000.

NWPPC (Northwest Power Planning Council). 1994. 1994 Columbia River Basin Fish and Wildlife Program. Northwest Power Planning Council, Portland, OR Document 94-55.

NWPPC (Northwest Power Planning Council). 1997. Consideration of ocean conditions in the Columbia River Basin Fish and Wildlife Program. NWPPC, Portland, OR. Issue paper 97-6.

NRC (Natural Resource Consultants). 1995. Database of propogated anadromous Pacific Salmon and Steelhead. prepared for the Northwest and Alaska Fisheries Science Center, NMFS, Seattle, WA.

Neal, V.T. 1972. Physical aspects of the Columbia River and its estuary. pp. 19-40. In. A.T. Pruter and D.L. Alverson (Ed.). The Columbia River estuary and adjacent ocean waters. Bioenvironmental Studies. Univ. Wash. Press, Seattle, WA.

Nichols, F.H., J.E. Cloern, S.N. Luoma, and D.H. Peterson. 1986. The modification of an estuary. Science 231: 567-573.

Northcote, T.G. and P.A. Larkin. 1989. The Fraser River: a major salmonine production system. p. 172-204. In D.P. Dodge (ed.). Proceedings of the International Large River Symposium. Can. Spec. Publ. Fish. Aquat. Scie. 106.

Olesiuk, P.F., P.E. Cottrell, and C.E. Neville. 1996. An assessment of Harbour seal (Phoca vitulina) predation on pre-spawning adult salmon in Comox Harbour and the lower Puntledge River, British Columbia. PSARC Working Paper S96-18. (Pacific Biological Station, Nanaimo, B.C.)

Orem. H.J. 1968. Discharge in the lower Columbia River basin, 1928-1965. USGS Circular 550: 24p.

Roby, D.D., D.P. Craig, K. Collis, and S.L. Adamany. 1998. Avian predation on juvenile salmonids in the lower Columbia River. 1997 Annual Report. submitted to BPA.

Scholz, N.L., N.K. Truelove, B.L. French, B.A. Berejikian, T.P. Quinn, E. Casillas, and T.K. Collier. 2000. Diazinon disrupts antipredator and homing behaviours in chinook salmon (Oncorhynchus tshawytscha). Can. J. Fish. Aquat. Sci. 57:1911-1918.

Seaman, M.H. (Ed). 1977. Columbia River Estuary Inventory of Physical, Biological, and Cultural Characteristics. Columbia River Estuary Study Taskforce, 750 Commercial St. Rm. 205, Astoria, OR 97103.

Sherwood, C.R. and J.S. Creager. 1990. Sedimentary geology of the Columbia River estuary. Prog. Oceanog. 25: 15-79.

Sherwood, C.R., D.A. Jay, R.B. Harvey, P. Hamilton, and C.A. Simenstad. 1990. Historical changes in the Columbia River estuary. Progress in Oceanography 25: 299-352.

Simenstad, C.A. 1997. The relationship of estuarine primary and secondary productivity to salmonid production: Bottleneck or window of opportunity? pp. 133-145. *In* Emmett, R.L. and M.H. Schiewe. Estuarine and Ocean Survival of Northeastern Pacific Salmon. NOAA Tech. Memorandum NMFS-NWFSC-29.

Simenstad, C.A., K.L. Fresh and E.O. Salo. 1982. The role of Puget Sound and Washington coastal estuarines in the life history of Pacific salmon: an unappreciated function. pp. 343-364. *In* V.S. Kennedy. Estuarine Comparisons. Academic Press.

Simenstad, C.A., D. Jay, C.D. McIntire, W. Nehlsen, C. Sherwood, and L. Small. 1984. The dynamics of the Columbia River estuarine ecosystem. Columbia River Data Development Program, 2 vol. 695 p. (CREST, 750 Commercial St. Rm. 205, Astoria, OR 97103).

Simenstad, C.A., L.F. Small, and C.D. McIntire. 1990. Consumption processes and food web structure in the Columbia River estuary. Progress in Oceanography 25: 271-297.

Simenstad, C.A., L.F. Small, C.D. McIntire, D.A. Jay, and C. Sherwood. 1990. Columbia River estuary studies: an introduction to the estuary, a brief history, and prior studies. Progress in Oceanography 25: 1-13.

Simenstad, C.A., D.A. Jay, and C.R. Sherwood. 1992. Impacts of watershed management on land-margin ecosystems: The Columbia River estuary. p. 266-306. In R.J. Naiman (editor), Watershed Management. Springer-Verlag, N.Y.

Small, L.F. (Ed.) 1990. Columbia River: Estuarine System. Progress in Oceanography (POCNAS) 25 (1-4): 1-358. Pergamon Press, NY.

Stehr, C.M., D.W. Brown, T. Hom, B.F. Anulacion, W.L. Reichert, and T.K. Collier. 2000. Exposure of juvenile chinook and chum salmon to chemical contaminants in the Hylebos waterway of Commencement Bay, Tacoma, Washington. J. Aquat. Ecosystem Health 00:1-13.

Stein, J.E., T. Hom, T.K. Collier, D.W. Brown, and U. Varanasi. 1995. Contaminant exposure and biochemical effects in outmigrant juvenile chinook salmon from urban and nonurban estuaries of Puget Sound, Washington. Environ. Toxicol. Chem. 14(6): 1019-1029.

Thomas, D.W. 1983. Changes in Columbia River estuary habitat types over the past century. CREDDP, Astoria, OR. 51pp. and appendices. (CREST, 750 Commercial St. Rm. 205, Astoria, OR 97103).

Tyus, H.M. and J.F. Saunders, III. 2000. Nonnative fish control and endangered fish recovery: lessons from the Colorado River. Fisheries 25(9):17-24.

U.S. Army Corps of Engineers. 1999. Columbia River channel improvement study. Final integrated feasibility report and environmental impact statement. Portland, OR.

WDFW & ODFW. 1999. Status Report. Columbia River fish runs and fisheries 1938-1998. Oregon Department of Fish and Wildlife.

Weitkamp, L.A. 1994. A review of the effects of dams on the Columbia River estuary environment, with special reference to salmonids. Bonneville Power Administration, PO Box 3621, Portland, OR 97208. DE-A179-93BP99021. 148p.

==

---

w:\em\ww\isab\1 isab final reports\isab 2000-5 estuary.doc