Development of a Conceptual Model for the Columbia River Navigation Channel Improvement Project Reconsultation Process

Prepared for Project Sponsor Ports

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Introduction

Development of a conceptual model was proposed at the first reconsultation workshop for the primary purpose of organizing the information on the Columbia River estuarine ecosystem. It was felt that by organizing the information the science panel and the other members of the management team would be able to see how various components of the ecosystem connect and potentially how actions associated with the dredging project could affect the ecosystem. The model would provide a tool to help guide discussions. As it stands now, there is a substantial array of information about the system and the project, but it is contained in lists and extensive text. The model would provide a simple diagram of the relationships among the various components of the ecosystem, and highlight the more important linkages. It would provide in simple graphic form the understanding of the ecosystem, as a well as be a guide for determining what types of data might be gathered during a monitoring program.

In general, a *conceptual model* is developed to ensure a shared vision of the relationship between components of the ecosystem. The conceptual model is used as formulation tool, a communications tool and an assessment tool. Properly constructed the conceptual model enhances stakeholder participation and minimizes ecological risk. Furthermore, coupling the conceptual model with a decision process and framework, allows the planning team to deal with risk and uncertainties in a systematic way. The combination of a conceptual model, and decision framework (which includes an assessment or monitoring component) is the essence of an adaptive management program. The conceptual model identifies on paper the connection between the actions associated with a project and the physical and biological reactions to these actions.

Aim of the Present Report

The aim of the present report is to assemble a simple but inclusive set of models that clearly identify the linkages in the biological portion of the Columbia River estuarine ecosystem, especially those that involve salmon. In addition, the models presented will provide a basis for linking the biological component of the ecosystem with physical and chemical requirements.

Estuarine Stressor Model

Stressors include natural and human-induced perturbations on the ecosystem that may have positive or negative impacts. The complex set of factors affecting the functional viability of

Pacific Northwest systems is illustrated in Figure 1 (Thom and Borde 1998). When viewing any project that might impact an estuarine system, the full suite of historical and recent changes should be considered. The state of knowledge does not allow for a cumulative assessment of multiple stressors at a level that can be easily modeled and predicted. Hence, we must rely on conceptual models to connect alterations with potential effects in the system.

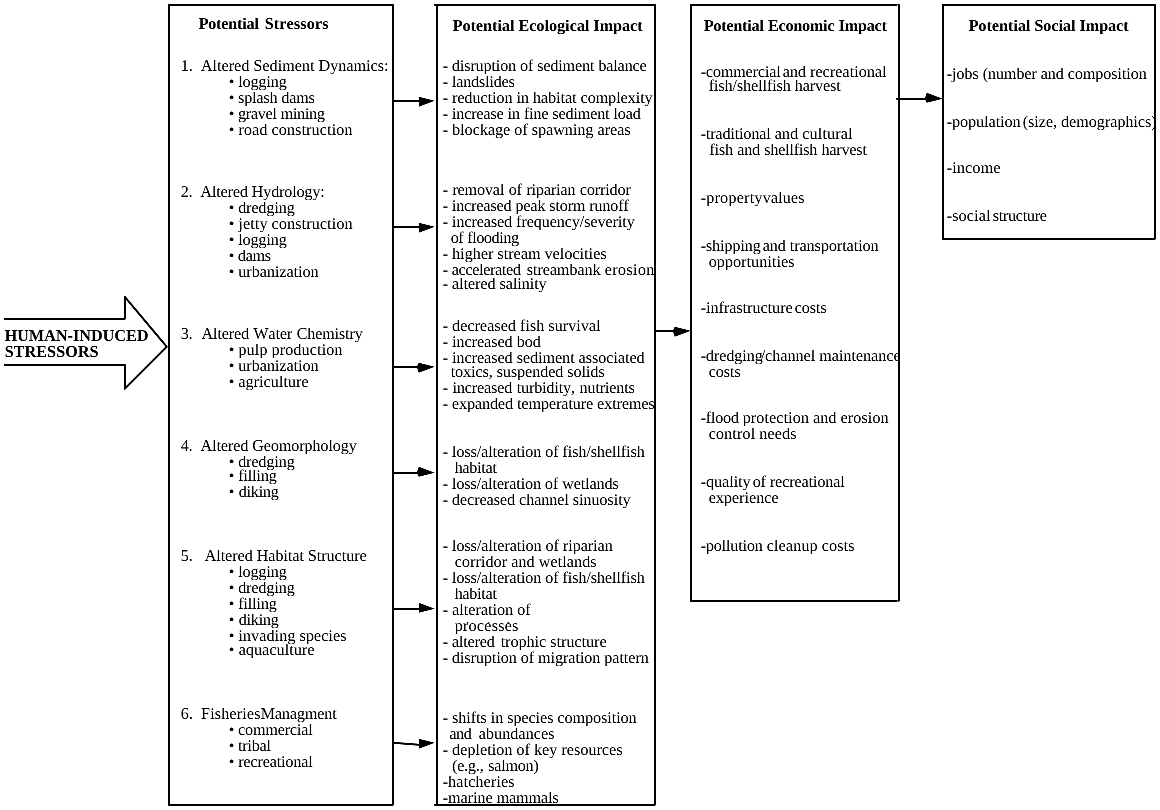


Figure 1. Stressors on estuaries of the Pacific Northwest (from Thom and Borde 1998).

General Form and Simple Example of a Conceptual Model

The general form of a conceptual model is as follows:

Controlling Factors →
Ecosystem Structure →
Ecosystem Function

Examples of controlling factors for a coastal marsh system in Puget Sound are shown in a simple conceptual model in Figure 2. The level of certainty about the quantitative relationship between the controlling factors and the structure of the system enters into the assessment of the uncertainty of the project. If there is a high degree of uncertainty about the relationship between a controlling factor and the structure of the system, and that this factor is believed to be highly important, there is good justification for focusing the best science into assessment of the relationship to reduce the uncertainty.

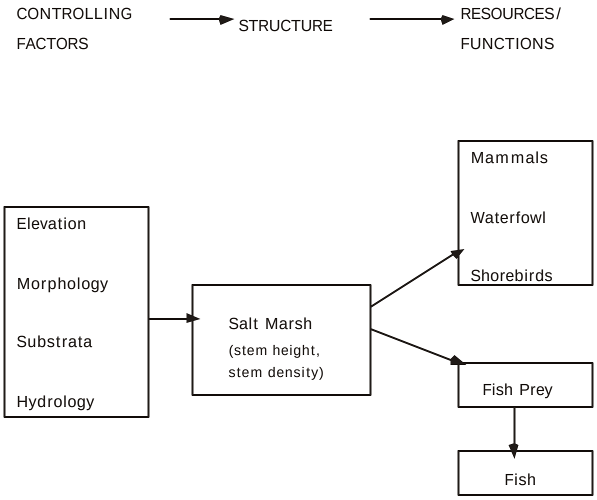


Figure 2. Simple conceptual model of a salt marsh system in Puget Sound

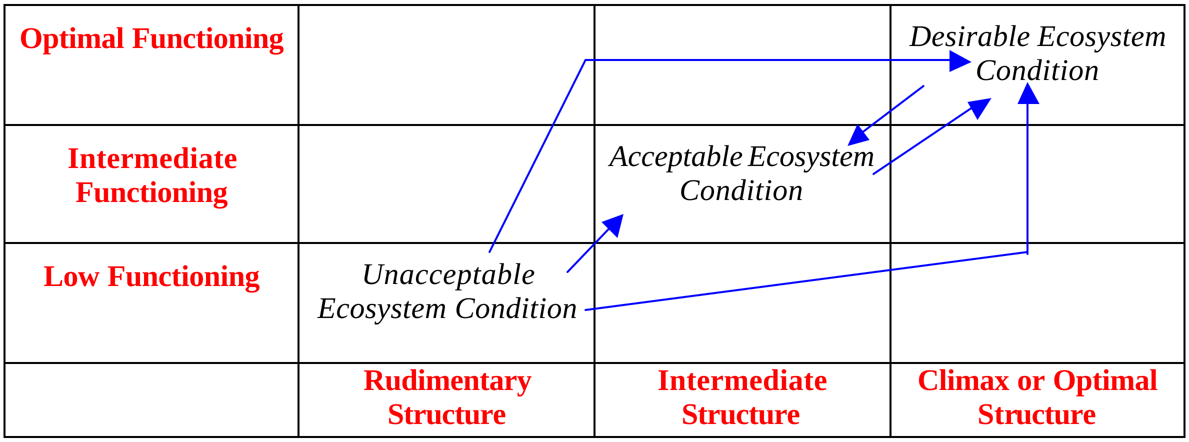
General Model for Ecosystem State

The conceptual can have application to the Columbia River estuary project reconsultation process by defining the historical, present and potential future state of the ecosystem relative to the project. The general model for ecosystem state is shown in Figure 3. First, it is assumed that there is a positive relationship between structure of an ecosystem and function of that ecosystem. The natural climax structure of an ecosystem, habitat or community has a corresponding and predictable functional condition. Under a restoration scenario, the goal would be to move the system from a condition of low functioning (and structural condition) to one that is either acceptable or desirable. Natural recovery of ecosystems will take place regardless of human intervention, but this may take a very long time (e.g., decades or centuries). Restoration essentially means that humans take actions that reduce the period of time required to reach improved ecosystem conditions. In reality this means that human intervention may set the system up to recover more quickly *using a combination* of physical intervention and natural recovery.

The levels of development are divided into low moderate and high in Figure 3. This essentially indicates that values (e.g., acreage) related to the structural condition (e.g., the size of the pond-wetland interface) and the functional conditions (e.g., the number of ducks nesting at this interface) can occupy a *range* (e.g., 80m^2 to 100m^2 pond-wetland area) as opposed to a single number. Hence, the goal for the project would be met if the system fell within a range of values for structure and function. Using a range of values *acknowledges two primary sources of uncertainty*:

- our ability to understand the relationship between structural and functional ecosystem components, and
- natural variability associated with structural conditions and functional conditions.

Under a restoration scenario, if the system occupies any set of values that are within the state identified as *Desirable Ecosystem Condition*, then it has met the goal. This approach recognizes that, because of uncertainties related to natural variability, influences from the surrounding landscape, and low predictive capabilities, we can reliably only get *close* to the target (Shreffler and Thom, 1993, Hobbs and Norton, 1996). This development model also indicates that if the system is not in the *Desirable* state that there are potential explanations, and that there are options for actions (Thom 1997, 2000). These explanations for the state of the system and actions are developed from the conceptual model. Therefore, incorporation of the conceptual model in conjunction with this development model provides one method to reduce the uncertainty.



Optimal Functioning			*Desirable Ecosystem Condition*
Intermediate Functioning		*Acceptable Ecosystem Condition*	
Low Functioning	*Unacceptable Ecosystem Condition*		
	Rudimentary Structure	**Intermediate Structure**	**Climax or Optimal Structure**

Figure 3. General model of ecosystem state. An ecosystem or habitat that is in rudimentary condition with low functioning develops into a system with optimal structure and functioning (after Thom 2000). Development can take several pathways, and can oscillate between system states.

Sources of Information

There is both a general belief that the Columbia River estuary is important, if not critical, to juveniles of some salmon species, and a lack of fundamental information proving this. According to Bottom et al. (2001, page 152), "…the intrinsic assumption that food or predation in the estuary may limit juvenile salmon productivity, or that there are carrying capacity limitations for juvenile salmon in the Columbia River estuary, has never been rigorously tested." In the opinion of Bottom et al., the complex relationships among the many factors affecting salmon, along with the primary producers in the food web, prey production and availability, and salmonid vulnerability to predators cannot be modeled in a straightforward manner.

Based on recommendations of people knowledgeable about the system, this white paper utilized the following list of publications in developing the conceptual model. These publications represent both primary reports of new research as well as synthesis documents.

An ecological characterization of the Pacific Northwest coastal region, volume one, conceptual model; volume three, characterization atlas, zone and habitat descriptions (Proctor et al. 1980). This set of publications represents a comprehensive compilation of information on estuarine and outer coastal systems in the Pacific Northwest. The presentation is organized by conceptual models of the various ecosystems in the region.

A review of the effects of dams on the Columbia River estuarine environment, with special reference to salmonids (Weitkamp 1994). This report includes a food web diagram including juvenile salmon.

Changes in fluxes in estuaries: implications from science to management (Dyer and Orth, editors, 1994). This book contains several papers on the Columbia River estuary from the team conducting research o the estuarine turbidity maximum.

Columbia River: estuarine system (Small, editor, 1990). This special publication in Progress of Oceanography, contains papers summarizing research conducted as part of the CREDDP program in the 1980's.

Salmon at river's end: the role of the estuary in the decline and recovery of the Columbia River salmon (Bottom et al. 2001). A comprehensive treatment of the factors contributing to changes in the role the estuary plays in juvenile salmon production.

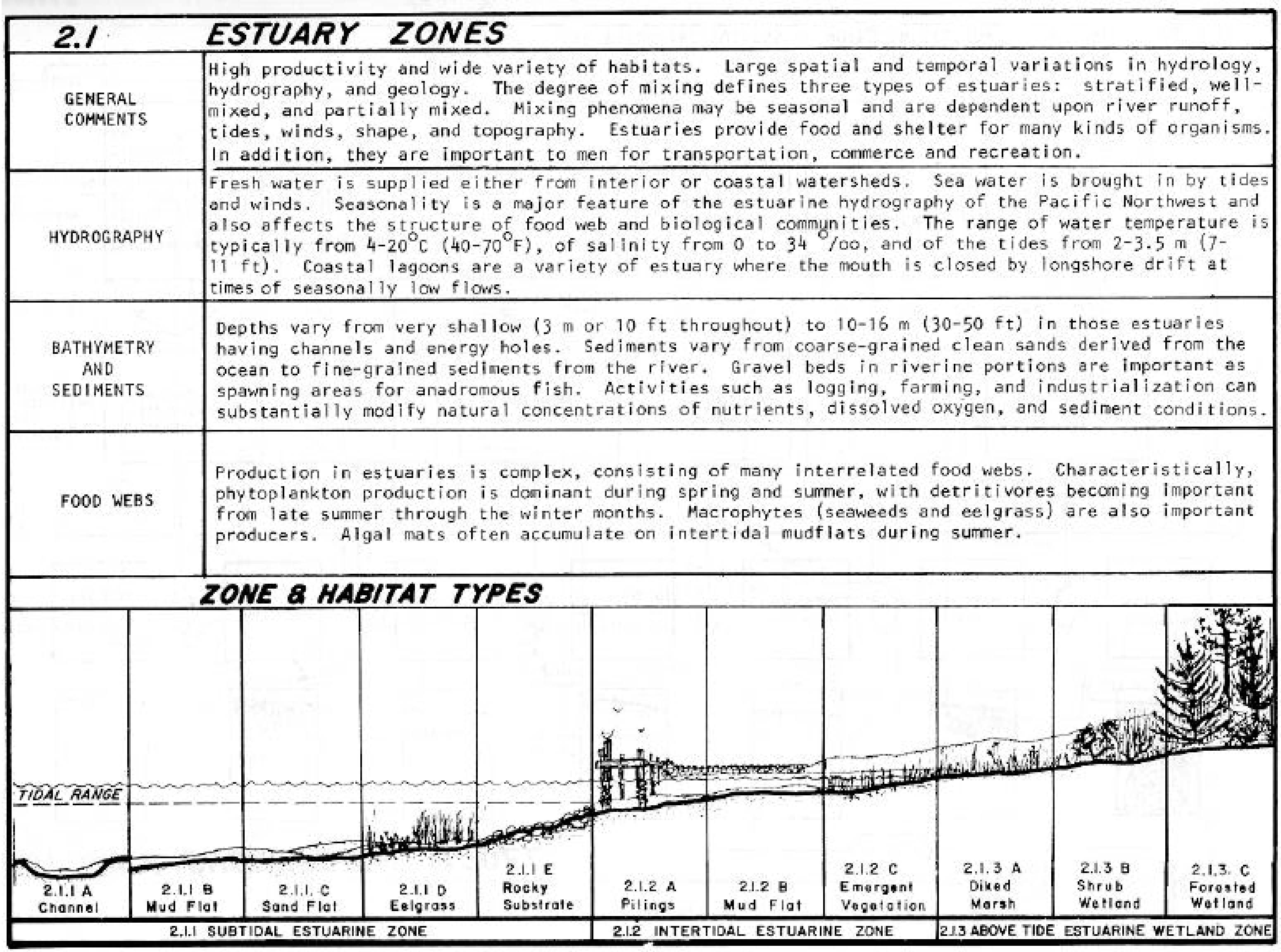
Chinook capacity to adapt to saltwater (Don E. Weitkamp, unpublished). Summarizes data on salinity and juvenile salmonids.

Prey consumed in estuaries (Don E. Weitkamp, unpublished). Summarizes knowledge on prey eaten by juvenile Pacific salmon in estuaries.

Columbia River Estuary Models

Proctor et al. (1980) provide a series of illustrations that summarize the fundamental picture of the Columbia river estuarine systems. In Figure 4 is shown the distribution of major estuarine habitat types and zones. The relative composition of some of these habitats has changed over the past 100 years, so that emergent wetlands and above-tide estuarine wetlands have been lost, and deep water habitats and flats and channels have increased in area.

The successional development of these habitats is dependent on several processes. As illustrated in Figure 5, succession proceeds with a subtidal mudflat or sandflat. Through physical processes of deposition and erosion, stabilization and siltation vegetation changes occur and the land surface elevation increases gradually forming forested wetlands and upland habitats (Proctor et al. 1980). Human-induced alterations of this successional process in the Columbia River estuary include diking, grazing, dredging and flow alteration (Sherwood et al. 1990). Since elevation and hydrology are key factors controlling the types of habitats and functions each habitat performs, altering primary and secondary rate controlling factors by restricting hydrology by diking, changing elevation by filling or dredging, or changing erosional and deposition processes by altering river flow or sediment supply will result in a modification of habitat distribution and function.



2.1 ESTUARY ZONES

GENERAL COMMENTS	High productivity and wide variety of habitats. Large spatial and temporal variations in hydrology, hydrography, and geology. The degree of mixing defines three types of estuaries: stratified, well-mixed, and partially mixed. Mixing phenomena may be seasonal and are dependent upon river runoff, tides, winds, shape, and topography. Estuaries provide food and shelter for many kinds of organisms. In addition, they are important to men for transportation, commerce and recreation.
HYDROGRAPHY	Fresh water is supplied either from interior or coastal watersheds. Sea water is brought in by tides and winds. Seasonality is a major feature of the estuarine hydrography of the Pacific Northwest and also affects the structure of food web and biological communities. The range of water temperature is typically from 4-20°C (40-70°F), of salinity from 0 to 34 °/oo, and of the tides from 2-3.5 m (7-11 ft). Coastal lagoons are a variety of estuary where the mouth is closed by longshore drift at times of seasonally low flows.
BATHYMETRY AND SEDIMENTS	Depths vary from very shallow (3 m or 10 ft throughout) to 10-16 m (30-50 ft) in those estuaries having channels and energy holes. Sediments vary from coarse-grained clean sands derived from the ocean to fine-grained sediments from the river. Gravel beds in riverine portions are important as spawning areas for anadromous fish. Activities such as logging, farming, and industrialization can substantially modify natural concentrations of nutrients, dissolved oxygen, and sediment conditions.
FOOD WEBS	Production in estuaries is complex, consisting of many interrelated food webs. Characteristically, phytoplankton production is dominant during spring and summer, with detritivores becoming important from late summer through the winter months. Macrophytes (seaweeds and eelgrass) are also important producers. Algal mats often accumulate on intertidal mudflats during summer.

ZONE & HABITAT TYPES

Figure 4. Illustration of general distribution of major estuarine habitat types in Pacific Northwest coastal estuaries (Proctor et al. 1980)

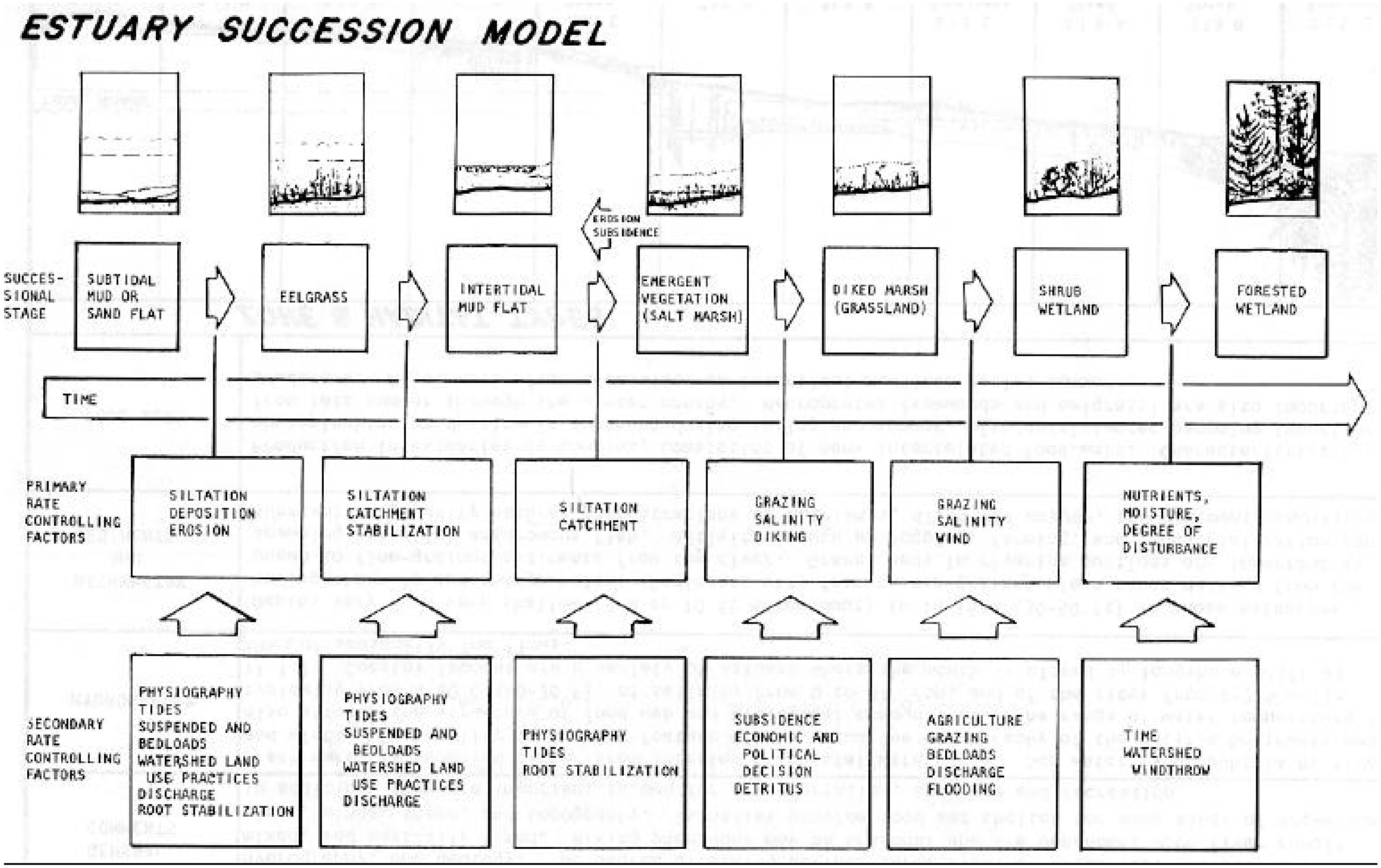


Figure 5. Diagram of successional processes and factors influencing habitat development in Pacific Northwest coastal estuaries (from Proctor et al. 1980).

Sherwood et al. (1990) summarized the changes that have occurred in the estuary (Sherwood et al. 1990). In their opinion, the tidal prism has been reduced approximately 15%, and there has been a net increase in sediment in the estuary. Sediment has eroded from the entrance and been deposited on the continental shelf. Reduced river flow has resulted in less mixing, increased stratification, altered the response to tidal forcing, and decreased salinity intrusion length and transport of salt into the estuary. There has been an estimated 82% reduction in emergent wetland production and a 15% reduction in benthic microalgae production. Riverine detritus derived from freshwater phytoplankton production has increased to partially compensate for this loss (Figure 6). This has caused a shift in the food web from macrodetritus from emergent marshes to more labile microdetritus from allocthonous phytoplankton. This shift has favored suspension feeding copepods associated with the turbidity maximum such as *Eurytemora affinis* and the harpacticoid copepod *Scottolana canadensis*. It is postulated that production of these species over benthic deposit-feeding invertebrates has resulted in a fundamental shift from support of a benthic feeding to a pelagic-feeding fish fauna. Estuarine-dependent juvenile salmon feed primarily on benthic prey, and this fundamental shift in the food web may have affected the quality and quantity of prey available to these fish.

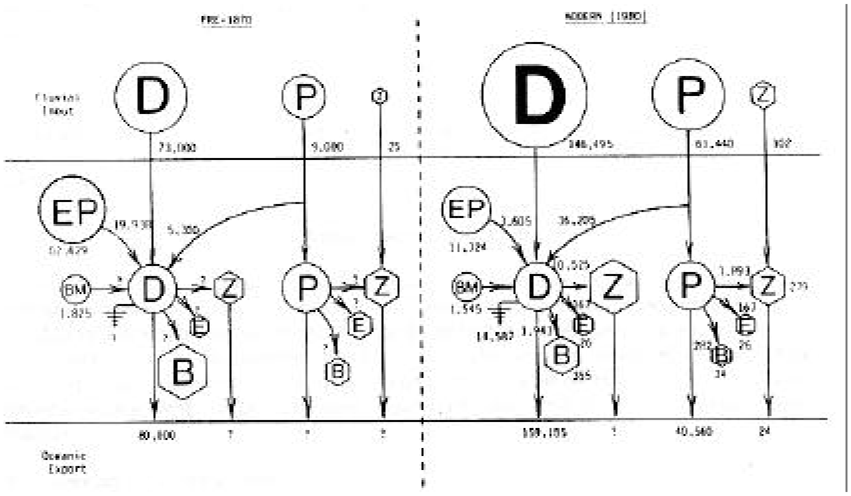


Figure 6. Postulated historical shifts in organic carbon sources (10^6 metric tons Carbon y^{-1}) and pathways for detritus-based food web in the Columbia River estuary (from Sherwood et al. 1990). D=water column detritus, P=phytoplankton, Z=zooplankton, EP=emergent plants, BM=benthic macroalgae, E=epibenthos, B=benthos (from Sherwodd et a. 1990).

The decrease in flows because of flow regulation has resulted in less variation in the location of the toe of the salt wedge as well as the location of the estuarine turbidity maximum (ETM). Extensive research on the ETM by Simenstad et al. (1994) and others indicates that the position of the ETM and the excursion of salty water are driven by tides and river flow (Figure 7). The ETM and salinity may play an important role in the food web as well as in structuring the benthic community (including important salmonid prey such as *Corophium*).

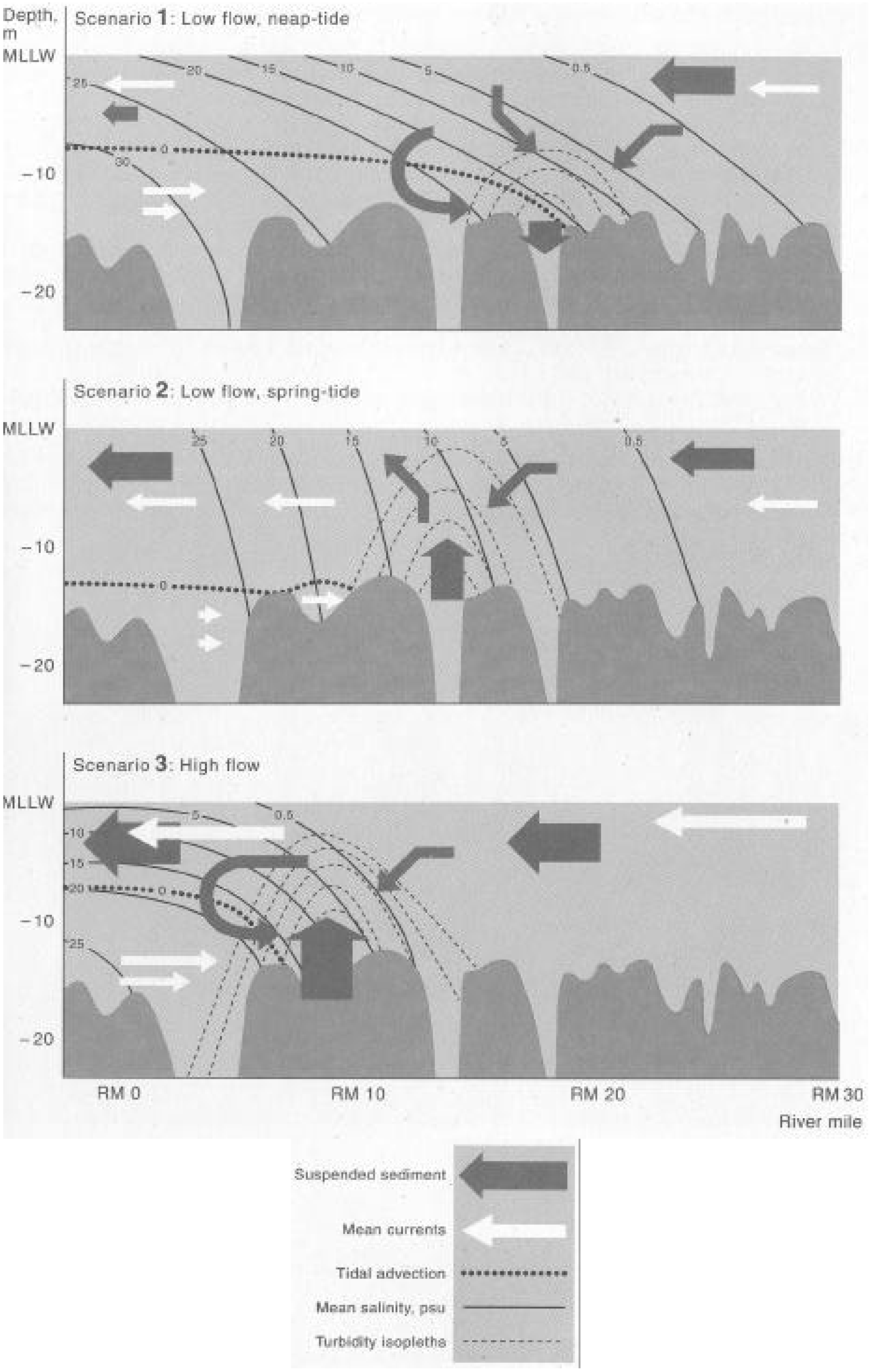


Figure 7. Generalized diagram of the estuarine turbidity maximum dynamics in the Columbia River estuary (from Simenstad et al. 1994).

Weitlkamp (1994) provides a food web for the estuary (Figure 8). The diagram highlights the sources of prey to salmonids in the estuary, which includes *Daphnia*, insects, mysids and *Corophium.* The latter three prey taxa are supported by marsh carbon, whereas *Daphnia* is supported by the resident phytoplankton and freshwater microdetritus pathway. It is important to note that the microdetritus pathyway supports a set of picivorous birds and mammals known to prey on juvenile salmon in the estuary. The degree to which this shift in the food web has affected salmonid production and survival is not quantified.

Bottom et al. (2001) proposed two criteria for evaluating changes in estuarine habitat and processes on subyearling, ocean-type, salmon physical habitat "opportunity". Their review of information on use of estuarine habitats in the Pacific Northwest indicated that *depth* and *velocity* were potentially useful in defining the areas most frequently utilized. These salmonids generallly were found in the depth zone of 0.1 to 2.0 m in the water column, and in areas where current velocities were on the order of 30 cm s^{-1} or less. These life-history types were generally oriented to shallow channels and marsh edges where benthic prey are abundant. Based on these criteria, Bottom et al. showed that habitat opportunity was altered because of bathymetry and flow changes in the system as compared to pre-dam conditions. Coupling their findings related to large scale alterations in flow characteristics with knowledge that loss of marshes and changes in sources of carbon that have occurred, they concluded that the productive capacity of the estuary has likely declined over the last century. They concluded (page 149) that, although the characterization of habitat opportunity needs to be further enhanced by refining the circulation model and broadening the suite of habitat indicators, "The results enable…novel and powerful ways to conceptualize habitat opportunity in the estuary, and its response to physical change."

The relationship between changes in the Columbia River and its estuary are complex. Bottom et al. (2001; page 29) present a comprehensive assessment of large scale historical changes in the estuary relative to salmon. However, evaluation of smaller scale changes, such as those relevant to the channel improvements project, is being approached from a variety of directions by various agencies. Some key issues that need to be included in this latter assessment are:

- Specific (especially shallow-water) habitats utilized during rearing and outmigration through the estuary
- Effects of physiochemical and biological conditions on estuarine residence times, growth, or survival
- Food chain relationships among juvenile salmon, invertebrate prey, and vertebrate predators
- Differences in these estuarine habitat needs and ecological relationships among salmon species, life-history types, and source populations.

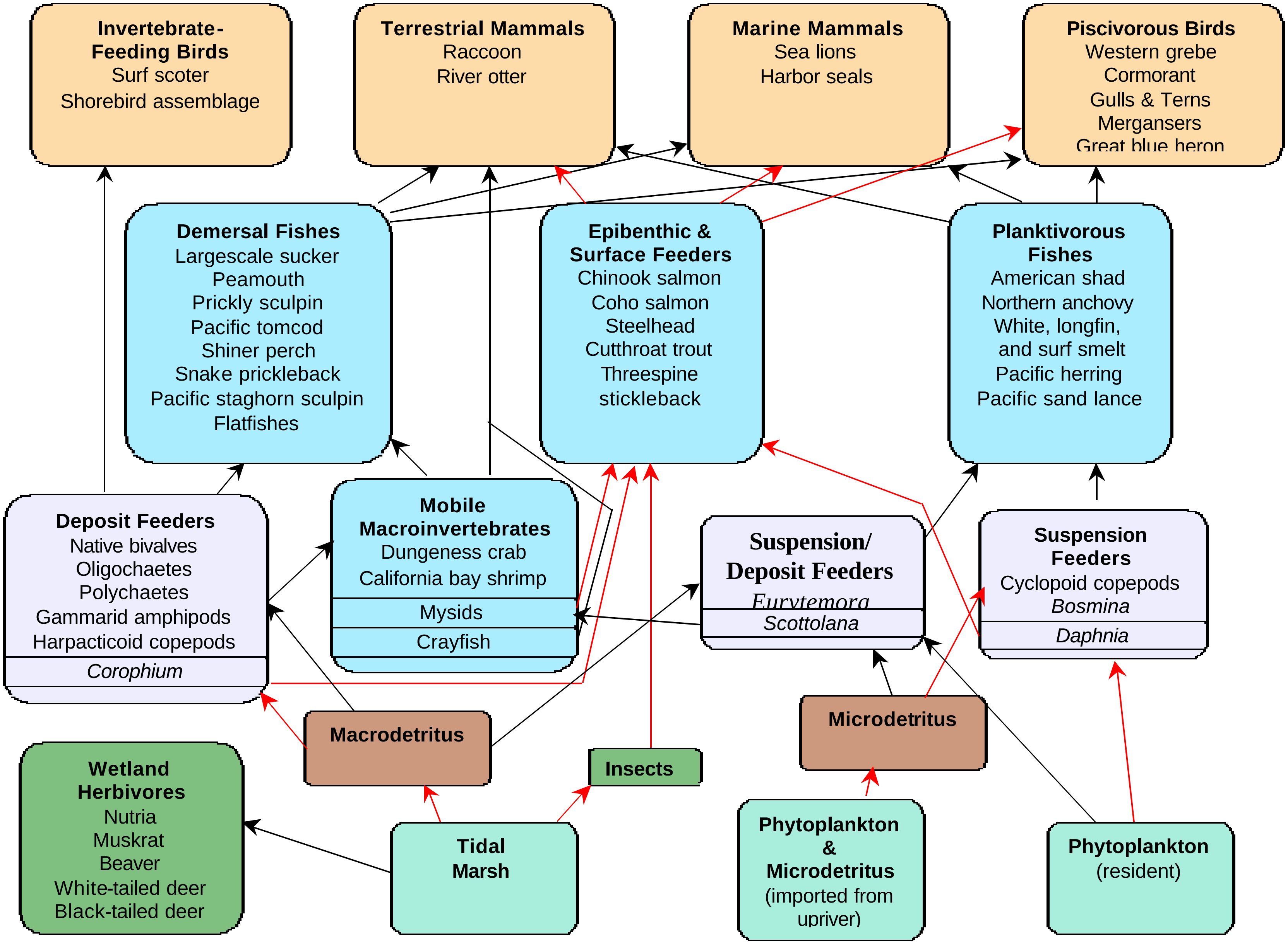


Figure 8. Simplified representation of the major linkages between trophic groups in the Columbia River estuary (from Weitkamp 1994). The red arrows show the pathways involving juvenile salmon.

Salmon-Centric Conceptual Model

Combined, the syntheses of information by Sherwood et al. (1990), Weitkamp (1994), Simenstad et al. (1994), and Bottom et al. (2001) on historical and present-day food webs, carbon sources, saliniity and ETM dynamics, and habitat opportunity relative to physcial conditions, provide a basis for a conceptual framework upon which to base potential changes in the estuary relative to a deeper navigation channel. The simple conceptual model of the factors affecting juvenile salmonid production in the estuary is shown in Figure 9. The model only indicates the major factors and does not illustrate direct and indirect connections or feedbacks. For example, salinity not only influences changes in salmon physiology but also influences the location and abundance of potential salmon prey. Among these prey taxa, the benthic amphipod *Corophium* represents an important component of the food web for salmon and its distribution may change depending on its salinity tolerances. Furthermore, the food available to *Corophium* may also change with altered salinity intrusion and altered habitat area (i.e., loss of marsh carbon), which will affect the productivity of the species. Three species of *Corophium* were reported by Jones et al. (1990) in the Columbia River estuary. One species (*C. brevis*) was restricted primarily to the River plume and ocean zone, whereas the other two (*C. salmonis*, *C. spinicorne*) were found over a wide range of salinity in from the tidal freshwater through the ocean zone. This indicates that this taxa group has a wide salinity tolerance.

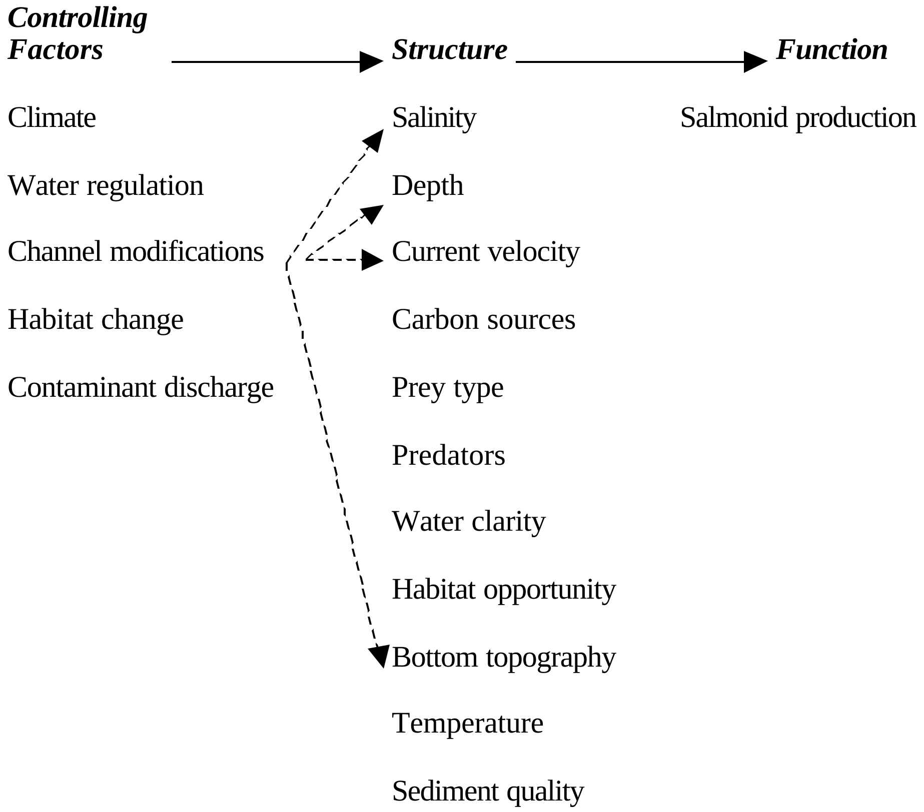


Figure 9. Conceptual model of factors controlling juvenile salmonid production in the Columbia River estuary. The dash line arrows indicate the potential direct influence of channel modifications on structural conditions.

Connecting Structural and Functional Components of the System to Assess Change

The structural components of the salmon ecosystem are summarized in Figure 10 and are related to the capacity of the estuary to support juvenile salmon. This figure generally follows the matrix of ecosystem state (Figure 7). In this case, we can piece together pre-dam conditions in the estuary at least qualitatively relative to the capacity of the estuary to support salmonids. The matrix does not account for changes in the life-history types in the system that have taken place over this period. According to Bottom et al. (2001), the capacity of the system is reduced from historical conditions primarily due to habitat loss, flow regulation and changes in carbon sources. Although reduction is flow has actually created shallow water habitat and refuge channels (i.e., habitat opportunity) in mid-portion of the estuary, a shift in dominance of the carbon source to allothonous microdetritus (which has only and indirect link to the salmon food web), has had a greater influence in reducing capacity. Predators have been a significant source of loss historically as they are under present conditions. However, the Caspian tern is now probably exerting more influence as compared to some other taxa.

One of the purposes of Figure 10 is to organize our understanding of the system in a simple manner that can be used to help make determinations on potential changes caused by the dredging project. The nine possible system states are identified, with states 1,5, and 9 being the predictable progression from a degraded condition to a fully functional undisturbed system. Other system states may have less probability of occurring, or may occur because we have not incorporated a key factor into the matrix. For example, if the system were completely undisturbed, but salmon capacity was only moderate (system state 6), there may be external factors such as overfishing, an oil sill, or a major climatic anomaly that reduced the capacity of the system. The fundamental question is wherther the project will move the system from its present condition to another state of conditions that are more or less favorable for juvenile salmon. The matrix acknowledges the fact that *there are ranges of conditions and related responses*, and that there *are uncertainties about the degree of change* that will actually show a significant response.

The single change with the project would be a deeper channel. This would have direct influence on bottom topography and salinity intrusion (Figure 9). These would in turn have potential effects on all other structural conditions. There are several related questions:

1. How well are these direct and indirect influences known?
2. What degree of change is predicted?
3. Will this change have on the current system state of the estuary?
4. What level of certainty must there be to make a determination?
5. Must the determination be based on quantitative data or on qualitative information?
6. What is the level of certainty about responses?
7. What should be done (i.e., mitigation, monitoring) under an adaptive management scenario to accommodate uncertainties?

These are the kind of scientific questions that can direct future technical discussions and suggest additional input for analysis.

Historical Capacity	*1*	*2*	*3. Greatest direct support and capacity*
Present Capacity	*4*	*5. Reduced direct support and capacity*	*6*
Further Altered Capacity	*7. Further reduced support and capacity*	*8*	*9*
	Further Altered Conditions	Present Conditions	Optimal Structure
Structural Component			
Salinity		-Salinity intrusion increased -Less spatial variability in location	-Highly spatially variable location
Depth criterion	0.1 - 2.0 m	0.1 - 2.0 m	0.1 -2.0 m
Current velocity criterion	Max. = 30 cm s^{-1}	Max. = 30 cm s^{-1}	Max. = 30 cm s^{-1}
Dominant carbon sources		-Allochthonous microdetritus -Autochthonous plankton -Marsh macro-detritus	-Marsh macro-detritus -Autochthonous plankton -Allochthonous microdetritus
Prey type		-Suspension/deposit feeders -Suspension feeders -Deposit feeders -Insects	-Deposit feeders -Insects -Mobile macroinvertebrates -Suspension/deposit feeders
Predators		-Significant (some different spp.)	-Significant
Water clarity		-Greater clarity and less variable?	-Lower clarity and more variable?
Habitat opportunity		-More tidal side-channels -Less marsh channels	-Marsh channels -Tidal side-channels
Bottom topography		-Deeper in outer estuary -Shallower in upper estuary -More side channels	-Shallower in outer estuary -Deeper in upper estuary -Fewer side channels
Temperature		-Warmer spring? -Cooler summer?	-Cooler spring? -Warmer summer?
Sediment quality		-Finer -Isolated contamination	-Coarser -Uncontaminated

Figure 10. Columbia River estuary capacity model for juvenile estuarine-dependent salmonids. The nine system states are indicated in the upper portion of the figure. The lower portion of the figure summarizes the conditions of the structural parameters within each structural state.

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