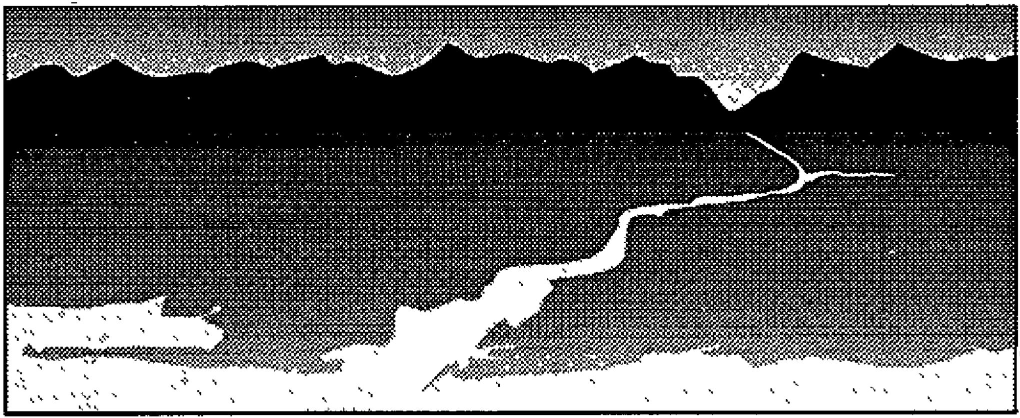
FINAL REPORT
8526-03

LOWER COLUMBIA RIVER



BI-STATE PROGRAM

RECONNAISSANCE SURVEY OF THE LOWER COLUMBIA RIVER

TASK 3 SUMMARY REPORT: REVIEW OF PHYSICAL AND HYDROLOGIC CHARACTERISTICS

JUNE 29, 1992

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TASK 3. SUMMARY REPORT REVIEW OF PHYSICAL AND HYDROLOGIC CHARACTERISTICS

By

Tetra Tech, Inc.

In Association With

Hartman & Associates
Keystone/NEA

For

Lower Columbia River Bi-State Program

June 29, 1992

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This document was prepared by Tetra Tech, Inc with assistance from Hartman & Associates Dr Ted Turk of Tetra Tech served as the Project Manager for all work conducted on the Columbia River Project Mr Greg Hartman served as the Task Manager for all the work conducted as part of *Task 3 Review of Physical and Hydrologic Characteristics*

Dr Tarang Khangaonkar of Tetra Tech was the principle author of the three reports that resulted from Task 3 Mr Jim Graham of Keystone NEA contributed significant sections to all the three reports. Mr Greg Hartman contributed to several sections and provided technical review Dr Khangaonkar and Mr. Greg Hartman provided the identification of data gaps and recommendations Illustrations were provided by Kim Shaty, and the word processing was performed by Ms Lisa Fosse and Ms Kelly Robinson

EXECUTIVE SUMMARY

This report summarizes the findings of a study on the hydrologic and physical characteristics of the lower Columbia River, from the Bonneville Dam to the river mouth. This study was one of six tasks undertaken as part of the Reconnaissance Survey of the lower Columbia River, initiated by the Bi-State Lower Columbia River Water Quality Program to assess the overall quality of the river. The goals of this study were to summarize existing data on physical characteristics, identify data gaps, and recommend models to predict the fate and transport of contaminants.

The Columbia River is the largest river in the United States to enter the Pacific Ocean. The river drains a large basin in six states and two provinces including much of Oregon and Washington. The Cascade range divides the basin into eastern and coastal sub-basins with different hydrologic and climatic characteristics. The heavy rainfall in the eastern basin in the winter and the snowmelt from the higher altitudes during the summer accounts for the high river discharge, which annually averages 260,000 cubic feet per second. Heavy winter rainfall in the coastal basin creates a secondary peak discharge from tributary flows into the lower Columbia River.

The river can be divided into three major regions: 1) the estuary region at the river mouth, 2) the upper river region, and 3) the transition region from the estuary to the upper river. Further subdivisions depend upon study requirements. Tides from the ocean enter the estuary region, and can reach as far upstream as the city of St. Helens during lower summer and fall river flows. The salinity influence from flood tides is limited to the estuary because of the high river discharge. The flow in the upper river is swift due to low resistance from physical features. The Columbia River transports large quantities of sediments and deposits about 35 percent of it in the estuary. The transported sediments are mostly fine sand and silt.

Pollution in the river is due to domestic, agricultural, and industrial wastes discharged into the river water. Effluents from various sources affect the water quality by adversely affecting the pH, temperature, and turbidity of the water and also by introducing toxic and radioactive chemicals into the river The pollutants are carried downstream either in dissolved form or in association with sediment particles in an adsorbed state

Relatively good data exists for the estuary, however, three large data gaps have been identified for other sections of the river 1) lack of sufficient current meter data or flow data on the Columbia River main stem at several locations above the estuary, where the flow bifurcates around the mid channel islands and near the mouths of various tributaries, 2) lack of sufficient sediment bed load and suspended load data for the entire length of the Lower Columbia River 3) lack of sediment characterization in secondary channels and backwater areas in the river upstream of the estuary

Water quality models attempt to predict the fate and transport of contaminants after they are introduced into a body of water. Numerical modeling of the lower Columbia River involves three major components 1) a flow model, 2) a sediment transport model, and 3) a contaminant transport model The flow model provides the necessary input to the sediment and contaminant transport models The transport models then predict the concentration of pollutants and sediments with respect to time and distance downstream

For modeling the lower Columbia River, a three-dimensional model in the estuary, a two-dimensional model in the intermediate region, and a one-dimensional branched model with two-dimensional modeling for site-specific reaches in the riverine region is recommended Tetra Tech recommends either a conservative approach using models that have already been applied and verified on parts of Columbia River, or a state-of-the-art approach using more sophisticated but untested models.

1.0 INTRODUCTION

1.1 THE BI-STATE PROGRAM

The states of Oregon and Washington are concerned that the water quality of the lower Columbia River has been impaired by toxic pollutants which enter the river through various outfalls and discharges There is also a high level of public concern over the water quality of the river Most of the prior studies and data collected by government, industries and educational institutions were aimed at specific purposes other than assessing the overall quality of the river The lack of information on the overall quality of the lower Columbia River from the Bonneville Dam to the river mouth, and the growing public concern regarding impaired river water quality underscored the need for additional studies The four year Bi-State Lower Columbia River Water Quality Program (Bi-State Program) was established at the direction of the legislators from the states of Washington and Oregon, to compile and collect water quality information on the lower Columbia River and make recommendations based on its findings

The Bi-State program for managing the lower Columbia River has the following goals

- To identify water quality problems
- To determine if beneficial/characteristic uses are impaired
- To develop solutions to the water quality problems
- To make recommendations on a long term Bi-State framework.

These goals are to be met by carrying out a number of tasks, including development of work plans for water quality studies, evaluation of existing data, performance of a reconnaissance survey, baseline studies, and advanced studies, and development of recommendations to regulatory agencies regarding the pollutant loading to the river

The primary objective of the first year of the Bi-State Program is to conduct a Reconnaissance Survey of the Lower Columbia River, to provide an initial assessment of the river's health

1.2 OBJECTIVES OF TASK 3

The reconnaissance survey of the lower Columbia River was split into six tasks, to be completed in the period extending from April 1991 to May 1992 One of the tasks was to review physical and hydrologic characteristics The objectives of this task were 1) to provide the physical and hydrologic characteristics of the lower Columbia River, 2) provide characteristics of the sediment transport and fate of sediments, 3) make recommendations on modeling approaches for the prediction of fate and transport of contaminants, and 4) recommend how the models could be applied to the Lower Columbia River system This task was divided into three subtasks, to be completed in the form of following reports

- Reconnaissance Survey of the Lower Columbia River: Task 3, Review of Hydraulic, Hydrologic, Sediment Transport, and Geomorphic Characteristics of the Lower Columbia River

- Reconnaissance Survey of the Lower Columbia River: Task 3, Report on Conceptual Modeling and Recommendations for Numerical Models.

- Reconnaissance Survey of the Lower Columbia River Task 3, Final Task Report and Recommendations

These three reports contain information on the transport mechanisms and capabilities of the Lower Columbia River with emphasis on eventual modeling of the physical system

This report forms the third report of the three mentioned above It summarizes the physical and hydrologic characteristics of the Lower Columbia River, summarizes the numerical strategies for modeling the water quality, and concludes with recommendations on numerical modeling approaches for future studies.

1.3 RELATIONSHIP OF TASK 3 WITH OTHER TASKS

The Reconnaissance Survey was split into the following tasks·

- Task 1 Existing Data Review
- Task 2 Pollution Sources
- Task 3 Hydrologic and physical Characterization
- Task 4 Biological Characterization
- Task 5 Beneficial Uses
- Task 6 Screening Survey

The hydrologic and physical characterization completed under Task 3, like all the other tasks, depends on the results from Task 1 to identify existing information on the hydrology of the river basin, flow characteristics, sediments, and pollutant data Based on review of the available data, river behavior and characteristics have been identified and recommendations have been made on selection of numerical models for prediction of channel flow, circulation, and sediment fate and transport The Task 3 reports, plus availability of data from Task 1 reports, have been compared to the data requirements for the level of modeling effort selected. This comparison has resulted in identification of further sampling requirements, which tie into Task 6 The data requirements for numerical modeling are directly proportional to the degree of modeling sophistication desired However, final recommendations on data sampling, specifically for the purpose of calibration of numerical models, cannot be provided until a decision is made by the state(s) on a future modeling approach

2.0 SUMMARY OF PREVIOUS TASK REPORTS

This chapter summarizes the findings of the earlier reports of Task 3, namely the hydrologic and physical characterization report and the numerical modeling report. The first report was written following a review of literature accumulated as a result of Task 1 Based on the studies by a number of investigators, the behavior of the river in terms of flow and sediment transport was characterized The numerical modeling report, on the other hand, was written primarily with future modeling in mind Therefore, much of the information on river and estuarine modeling was based on studies performed at locations other than the lower Columbia River itself The modeling studies that have been performed on the river are limited and are discussed in the report on numerical modeling

2.1 SUBTASK 1: HYDROLOGIC AND PHYSICAL CHARACTERISTICS SUMMARY

In this subtask, existing information on the physical and hydrological characteristics of the lower Columbia River was identified and summarized A great deal of existing information was gathered through review of reports and files of the U S Army Corps of Engineers (COE) and U S. Geological Survey (USGS), as well as other federal, state, and local agencies In addition, interviews were conducted with personnel at these agencies who have extensive knowledge and experience on the Columbia River There have been several major programs, such as the Columbia River Estuary Data Development Program (CREDDP), and physical and numerical modeling studies performed by the COE, which have resulted in a thorough characterization of certain processes and locations within the lower Columbia River.

The following sections summarize the findings of subtask 1, the review of hydrologic and physical characteristics

2.1.1 River Segmentation

The physical processes of the lower Columbia River vary considerably as the river is transformed from a riverine to an estuarine environment The river widens from approximately 2,100 feet at River Mile (RM) 53 to about 47,000 feet in some reaches of the estuary Associated with the width changes is a variation in river velocity and sediment transport capability Other changes that occur in the lower river and estuary include increased tidal influence and the presence of a saltwater wedge

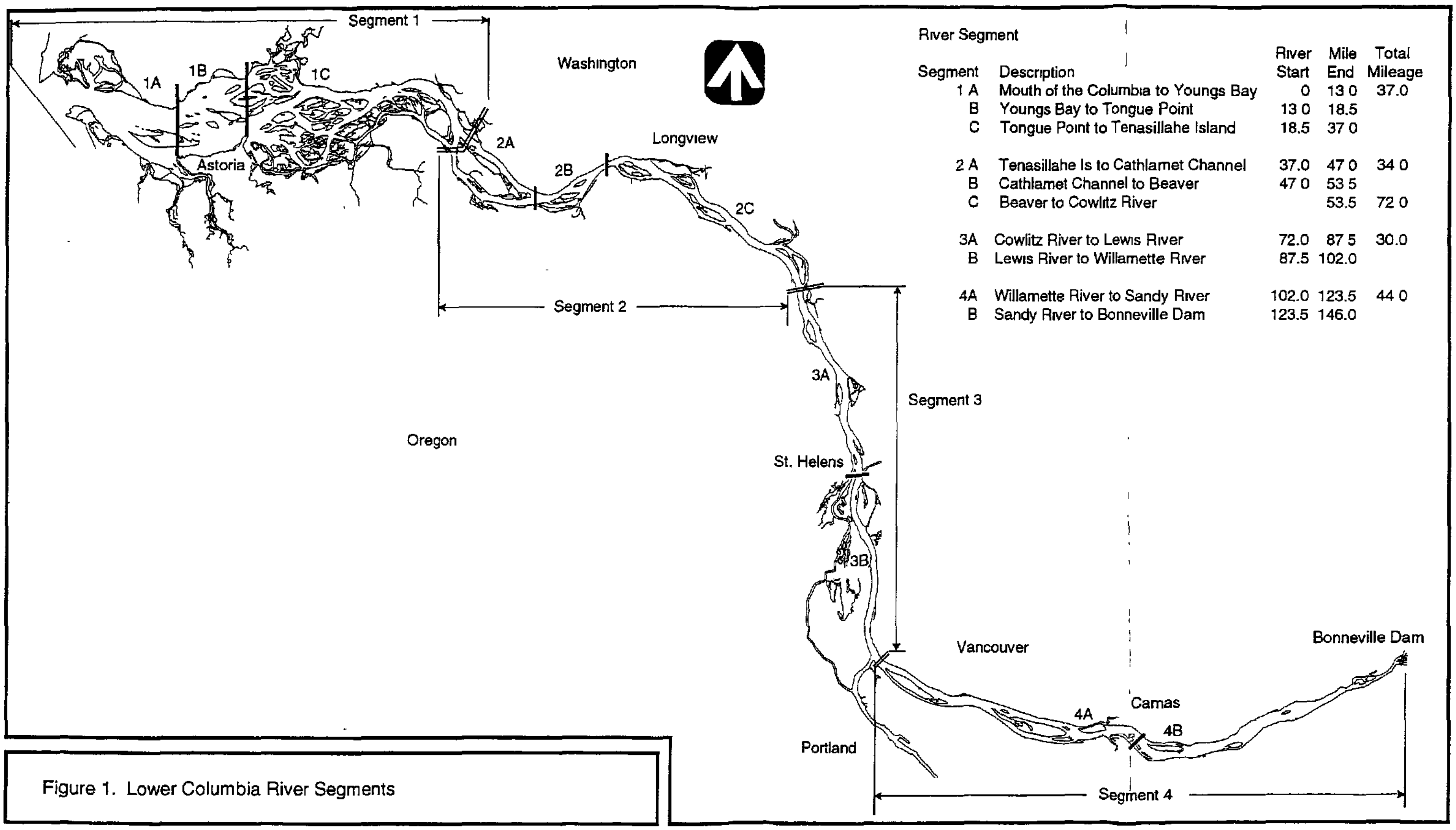
During the course of the Task 3 study, two useful classifications were developed for subdividing the river into similar reaches or segments Figure 1 shows the Lower Columbia River base map with segmentation used for Subtask 1 The first classification (Subtask 1) was based on physical or political characteristics This classification was necessary because of the project-specific nature of much of the existing data. Field sampling (Task 6) was prioritized within each segment to fill gaps in the existing data The second classification (Subtask 2) was developed for modeling purposes, dividing the lower Columbia River into segments for which different types of models were appropriate The river segmentation by river mile for the two classification schemes is shown below

Segment No	Subtask 1	Subtask 2
1	0-37	0-37
2	37-72	37-54
3	72-102	54-146
4	102-146	

In the following sections, the physical properties of the lower Columbia River are discussed with respect to segmentation

2.1.2 Hydrogeologic Characteristics

The Columbia River is the largest river to discharge to the Pacific Ocean. The Columbia River drains about 258,000 square miles of the northwestern United States and southwestern Canada The river has a distinct bi-modal flood season The largest floods are associated with flow from the upper Columbia River. Upstream of Bonneville Dam, floods are caused by springtime snowmelt in areas generally east of the Cascade Divide between April and June. Wintertime rainstorms in areas west of the Cascade



River Segment

Segment	Description	River Start	Mile End	Total Mileage
1 A	Mouth of the Columbia to Youngs Bay	0	13.0	37.0
B	Youngs Bay to Tongue Point	13.0	18.5	
C	Tongue Point to Tenasillahe Island	18.5	37.0	
2 A	Tenasillahe Is to Cathlamet Channel	37.0	47.0	34.0
B	Cathlamet Channel to Beaver	47.0	53.5	
C	Beaver to Cowlitz River		53.5	72.0
3A	Cowlitz River to Lewis River	72.0	87.5	30.0
B	Lewis River to Willamette River	87.5	102.0	
4A	Willamette River to Sandy River	102.0	123.5	44.0
B	Sandy River to Bonneville Dam	123.5	146.0	

Figure 1. Lower Columbia River Segments

Divide cause winter floods that equal or exceed the mean during the period from November through March The lowest discharges occur during September and October (Simenstad 1990)

River flow in the upper Columbia is heavily regulated Above the Bonneville Dam, there are 52 multipurpose projects located on the Columbia River and/or its major tributaries Project storage exceeds 35 percent of annual flow (COE 1986) The average annual discharge on the main stem above Bonneville is about 194,000 cubic feet per second (cfs) The average annual discharge at the mouth of the estuary approaches 260,000 cfs The Willamette River is the major tributary on the Columbia River, discharging into the Columbia River at RM-101 The Willamette River average discharge approaches 35,000 cfs Maximum daily discharge conditions during the winter have reached 280,000 cfs (USGS 1990), this flow was exceeded during the flood event of 1964.

The lower Columbia River is classified as a lowland river with a low gradient approaching 0 001 percent Tidal impacts related to river stage are noted throughout the study area and flow reversals have been detected as far upstream as RM-95 (Eriksen, personal communication, August 1991) Major flow reversals of significant time duration relative to sediment transport impacts are not expected upstream of Segment 2 (RM-72) The salt-water wedge reaches up to RM-27 during low flows and neap tide, with a 7 to 10 mile difference between high and low freshwater discharge (Jay 1984) During ebb tide and high river discharge, the salt wedge can be advected completely out of the estuary

2.1.3 Hydraulic Characteristics

The dominant hydraulic characteristic of the lower river is the relatively high velocity of the river during most conditions. Velocities greater than 5 ft/sec occur during average flood stage even though the bed slope in the river is low (approaching 0 001 percent), largely due to the high discharge and low resistance to flow

Downstream velocities in all four segments are moderated at low flow (less than 150,000 cfs) by tidal conditions During high discharge (greater than 300,000 cfs), the salinity intrusion can extend up to RM-14 in the estuary. Complex conditions in the estuary consist of three-dimensional flows through deep channels of variable salinity, which meander past shallow bays, flats and islands in a wide coastal plain-type estuary These conditions make the measurement and prediction of current directions and velocities (a necessity for contaminant transport predictions) extremely complex The tidal flow takes place mainly through the north channels of the estuary, while the river flow occurs along the deep thread of the estuary, confined by the navigational channel River conditions upstream of the estuary tend to be relatively less complex, with a typical uni-directional flow The presence of multiple channels, tributary influence, and tidal moderation must be considered in model selection

2.1.4 Sediment Transport

Sediment transport and fate is important because of the affinity of many contaminants to fine sediments, typically smaller than very fine sand grain sizes (i e , less than 0 08 millimeters) Applying modeling techniques to better under sediment transport and deposition processes will allow identification of contaminant sources and determination of contaminant impacts Knowledge of sediment transport is also required to predict dredging activities related to maintenance of the navigation channel The lower Columbia River transports significant amounts of sediment which are sand-sized and smaller The transport mechanism is either as suspended sediments (fine silt and clay) or as bed load (sand) Throughout the lower Columbia River, fine sediments will be deposited only in low energy environments located in sloughs, back channels, and within the estuary

Jay and Good (1978) and Haushild (1966) have estimated that the total suspended load of fine grain sediments in the lower Columbia River averages approximately 10 million tons/year. Following the eruption of Mt St. Helens in 1980, the suspended load measured at Longview (RM-67) increased by an estimated 41 percent. Deposits of fine grain silt and clay sediment were found to be limited in the river upstream of Segment 1. Greater than 86 percent of the bed covered with waves varying from 3 to 11 ft high, and 60 to 325 ft long (McAnally 1983) These waves migrate downstream during periods of medium and high flows. The strong river currents and predominant presence of sand on the river bed suggests that the fate and deposition of fine sediments in the upper river is temporary and limited in area However, fate of fine sediments in the estuary which forms a sink for the fine sediments transported downstream is of concern.

It is estimated that 20 to 35 percent of the suspended sediments transported to the estuary from upstream are retained, approximately 2 to 3.5 million tons per year. A range of 1 to 2 million tons of sand per year is estimated to enter the estuary as bed load (Whetten 1969, Ogden Beeman Associates 1984) Researchers such as Hubbell (1971), Gross (1972), and Nittrouer (1978) have estimated that approximately 35 percent of total sediment load (approximately 3-4 million tons/year) is deposited in the estuary

The Columbia River Estuary bed is principally fine sand-sized sediment (0 5 mm to 0 125 mm) with a mean size of 0 17 mm, and a few sheltered or shallow water areas that are silt-sized (COE 1983) The bed material texture demonstrates seasonal variations, with sediments tending to be finer near the end of a low flow period and coarser after a high discharge (Sherwood and Craeger 1990) Discharges approaching 500,000 cfs and higher will transport sand beyond the mouth (COE 1986)

2.1.5 Geomorphic Characteristics

The geomorphology of the lower Columbia River may be characterized as an extremely straight alluvial channel with numerous mid-channel bars and islands Most of the bank material in the lower river is non-cohesive silty sand and is extremely susceptible to bank erosion High current velocities are directed towards the erodible banks These conditions coupled with virtual elimination of natural sediment load replenishment from upstream of Bonneville Dam, have resulted in an increased rate of bank erosion (COE 1986) The main navigation channel is dredged to a much greater depth than natural conditions, which may in turn result in further changes in river morphology As the river velocity slows in the vicinity of the estuary, it deposits much of its sediment load This sediment deposition process has resulted in the formation of a wide, multichannel river, with bifurcations and diverse sediment sizes

2.2 SUBTASK 2. MODELING REPORT

The approach to the numerical modeling report was to 1) identify the modeling studies on the lower Columbia River, 2) identify state-of-the-art river models, based on up-to-date investigations on similar river and estuary systems, and 3) select and recommend the models that best suit the study requirements The following sections summarize the findings of the Subtask 2

2.2.1 Conceptual Model

There are a number of complex physical processes that occur in a dynamic water way such as the lower Columbia River A conceptual model attempts to simplify many complex physical processes into simple mechanisms that are amenable to mathematical analysis and numerical solution The motion of water in the lower Columbia River is affected by several processes

- **River Discharge** - Total upstream discharge is directly responsible for the net flow downstream The upstream discharge is dependent upon the releases from flow storage facilities, discharges from the tributaries, and hydrologic and meteorological parameters

- **Gravitational Force and Resistance** - The gravitational force is responsible for inducing the downstream river flow The parameters governing the gravitational effect on the flow are the slope of the river bed and the free surface slope (depends on discharge, tide and bathymetry) of the river River bed friction, which depends on flow velocities, opposes the flow and results in transport of sediments with the flow

- **Geography** - Rivers with large curvatures are affected by the force of Coriolis, the strength of this force is dependent on the latitude and flow velocity Bottom slope affects flow velocities, and bottom topography and land boundaries are responsible for the fine structure of the flow

- **Nontidal Oceanic Influence** - The flow at the mouth of the river is affected by waves that refract into the estuary and affect the sedimentation

- **Tidal Oceanic Influence** - The tide entering the mouth of the estuary is a major source of energy for the circulatory processes in the estuary. The effects of tides may be felt beyond the confines of the estuary in the form of rise and fall of the river water surface, flow reversals, and variations in flow with tidal period

- **Atmospheric Interaction Processes** - Wind and barometric pressures may affect the flow in the estuary area where the water surface area is large.

These parameters are the driving forces that cause or directly affect the motion of the river water A hydrodynamic flow model numerically defines these parameters, uses the bathymetric and flow data, and predicts 1) flow velocities, 2) circulation patterns, 3) river elevations, and 4) bottom shear, based on the driving forces.

Water quality at a point along the river depends upon the flow at that location and the constituent loading Constituents under consideration may include dissolved chemicals, sediments, or suspended particles from outfalls The river flow transports the dissolved and suspended particles downstream by way of advection and diffusion Bottom shear and turbulence induces the motion of sediments which are carried downstream by way of bed load or suspended transport A sediment transport model uses the flow data and the upstream sediment loading to compute the sediment movement Similarly, a contaminant transport model predicts the pollutant concentration downstream using the flow and pollutant loading data

These processes can be simplified by a simple conceptual model (Figure 2) The primary driving forces for the Columbia River, the tides and upstream discharge, determine the river flow structure, which in turn is controlled by river geometry The flow structure is given by the flow model, although the flow model used need not be the same over the entire reach of the river The results of the flow model are used as inputs to the sediment and pollutant transport models The results of pollutant and sediment transport models may be used to study 1) shoaling characteristics of the river, 2) concentration of toxic elements, 3) biological oxygen demand (BOD) and dissolved oxygen (DO) concentrations, 4) fate of settleable particles and phytoplankton growth Thus, simulation of river health or river water quality requires simulating river flow, which can be related to constituent transport for determination of fate of contaminants and transport of any other conservative substances

2.2.2 River Hydrodynamics

Accurate flow simulation is essential for determining the temporal and spatial characteristics of constituent transport with reasonable accuracy. Logically, the most sophisticated models should be applied for flow simulation and constituent transport. However, selection of a model depends upon the appropriateness of the model and the costs of applying the model to a particular river reach Due to geometric variations, bathymetric effects, and tidal and river flow influence, there is not one ideal model for the entire lower Columbia River from Bonneville Dam to the river mouth Based on hydrodynamic flow behavior, the river is divided into 1) estuary region, 2) intermediate region, and 3) riverine region

Estuary Region: RM-0 to RM-37 Hydrodynamically, the estuary region is the most complex reach of the river The estuary has a wide mouth (about two miles in width) which is open to salt wedge intrusions. Freshwater river flow averages about 260,000 cfs and is highly modified by the tides. The flow structure depends on the bathymetry, which is diverse and includes shoals and small islands The

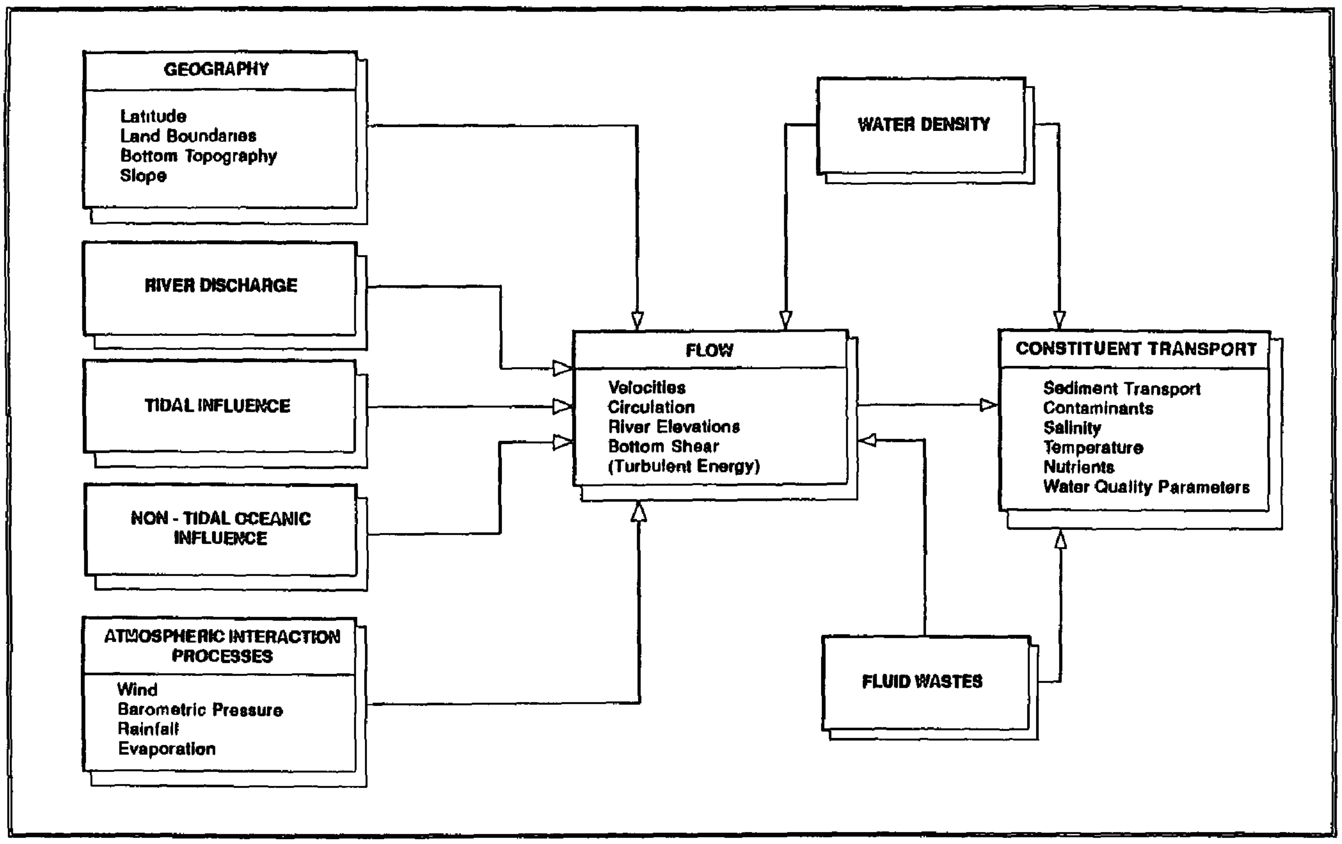


Figure 2. General Conceptual Model Framework for Physical Processes

vertical flow structure is also affected by salinity-induced stratification Due to the dominance of river flow, more mixing occurs during the ebb than the flood tide, which affects salt water and fresh water stratification Salt transport in and out of the estuary occurs along different paths These hydrodynamic characteristics, which indicate a strong three-dimensional flow structure, support application of a fully three-dimensional model in the estuary region

Intermediate Region: RM-37 to RM-54 The intermediate region of the lower Columbia region is the transition region, where the flow changes from riverine to tidal The flow is affected by the tides, and flow reversals have been observed However, there is no salinity in this region; therefore, no vertical stratification exists. Throughout the region, there exists a number of multiple channel reaches, and the flow is split between them The main channel, often referred to as the navigational channel, supports most of the flow Due to a lack of vertical stratification, the flow can be assumed to be uniform in the vertical direction, but the islands and navigational channel induce a lateral variation that cannot be ignored This region requires a vertically averaged, horizontal two-dimensional model to obtain sufficient accuracy in numerical simulation

River Flow Region: RM-54 to RM-146 In this region, the river exhibits dynamic open channel flow for the most part. The channel bed slope is negligible and the flow is governed by upstream discharge from the Bonneville Dam and inflow from the tributaries The variations in flow and transport parameters are much higher along the river than in the vertical or the lateral directions, and the simplest approach is to assume one-dimensional, quasi-steady-state conditions, assuming steady state conditions over short durations However, the lower Columbia River shows tidal effects in the form of flow reversals as high as RM-95, therefore, a dynamic (time dependent) model is recommended While most of the flow is in the navigational channel, localized areas with sloughs and islands create a lateral variation This would require a two-dimensional model for simulation Thus, this reach of river may be modeled using an open-channel, unsteady one-dimensional model, with additional localized analysis using two-dimensional models where necessary

2.2.3 Pollutant Modeling

River contamination results from three principal sources of pollution 1) point sources, 2) non-point sources, and 3) in-place pollutants Point sources are those discrete pollution sources that discharge directly to the waters of the lower Columbia River They include domestic, industrial, and agricultural facilities that discharge effluent directly into the river via outfalls. Non-point pollution sources represent pollution that enters the river from dispersed water-based or land-use activities in counties bordering the river Non-point sources include sources of pollution which are difficult to quantify because of their mechanisms of transport (surface run-off, groundwater transport, atmospheric deposition). In-place pollutants are those that are already present in the river like contaminated sediments which may release pollutants to the water column. In-place pollutants which may contribute to non-point sources include hazardous waste sites and sanitary landfills located near the river (Tetra Tech, 1992a)

The primary factors influencing water quality variables include 1) quantity of effluent discharge, 2) water depth, and 3) flow These factors influence temperature, pH, turbidity, BOD, DO, phytoplankton growth, conductivity, trace metals, radionuclides, and other toxic compounds or minerals

The transport of contaminants via the river flow occurs in three phases 1) dissolved phase, 2) suspended phase, and 3) sediment phase The portion of the contaminants that are dissolved into water are carried downstream with the river flow by the process of advection and diffusion Suspended particles of waste are carried downstream mainly by advection with the flow and to certain extent by dispersion Part of the effluent dissolved phase is adsorbed into fine-grained bottom sediments and becomes part of the suspended sediments that are transported downstream via river fluvial transport

Thus, pollutant modeling requires three models 1) a hydrodynamic flow model, 2) a contaminant transport model, and 3) a sediment transport model The flow directly carries the dissolved component by way of mass transport and diffusion, so a numerical model is required that solves the advection-diffusion equation using the flow results of the hydrodynamic model. Similarly, the sediment transport model requires input from the hydrodynamic model to compute the transport of bed sediment as a combination of bed load and suspended load.

2.2.4 Numerical Models of Flow and Transport

Modeling techniques, aided by advances in the computational power of the new generation of computers, have reached a high level of sophistication and accuracy The simplest models are the one-dimensional models that assume a completely mixed flow. Callaway (1970) used such a model to simulate the flow in the Columbia River from Bonneville Dam to the river mouth. The next level of sophistication consists of two-dimensional models that assume uniformity in one direction and variability in the other direction

The Columbia River Hybrid System (McAnally 1983) uses a two-dimensional flow and sediment transport model, calibrated by using a physical scale model of the estuary to study flows and sand movement in the estuary. A quasi-three-dimensional model of the estuary has been constructed by Hamilton (1984), who uses a combination of a two-dimensional model in the vertical direction and a network of branched channels to model the hydrodynamics of the estuary.

A number of new hydrodynamic models have appeared in the market, which consider full three dimensional variations of flow with minimum approximations. Similarly, three-dimensional models of pollutant dispersion and sediment transport are now available. These models have been reviewed by Tetra Tech (1992b) in a report on numerical modeling. The task of producing a state-of-the-art, three-dimensional numerical modeling package for rivers and estuaries is being pursued by the Waterways Experiment Station in Vicksburg, Massachusetts (Robey and Lower 1991).

3.0 DATA AVAILABILITY AND GAPS

The identification of data gaps is an important component of scoping future studies on the Columbia River Data gaps are identified by evaluating the existing data and determining what additional data are required to characterize the river, develop a better understanding of the physical processes, and perform numerical modeling studies Sufficient data exists for a qualitative understanding of the river behavior Available information is summarized in the Task 3 report, *Hydraulic, Hydrologic, Sediment Transport and Geomorphic Characteristics of the Lower Columbia River*

Data needs for numerical modeling purposes depend upon the modeling sophistication desired Two potential modeling approaches are discussed in Section 4 0, a conservative approach and a state-of-the-art approach The data needs will depend upon the approach selected As a result, this discussion of data gaps has been developed assuming a generic modeling approach

To develop a numerical model that is capable of simulating the hydrodynamics, sediment transport, and contaminant transport, the modeler must have sufficient knowledge of the following

- Bathymetry
- Tides
- Flow from Bonneville Dam and major tributaries
- Sediment transport and dredging records
- Salinity and temperature data

3.1 BATHYMETRY

Water depth as a function of location is a requirement for any type of model Bathymetry of the lower Columbia River is complex, with a number of mid-channel islands and sand shoals which vary in size, location and shape

The bathymetry data can be obtained through the COE surveys of the navigation channel and the Vancouver to the Dalles navigation projects The surveys are in the form of transects across the channel at 500 ft intervals Data are needed for the regions beyond the navigated channel, which are not covered by the surveys (COE 1991, COE 1987)

Although flow from Bonneville Dam and tributaries from RM-146 to RM-54 is mostly supported by the navigational channel, predominant settlement of fine grain sediments is outside the main channel in backwater and secondary channels The fine grain sediments are of concern because of contaminant affinity to these particles Modeling of backwater flow and sedimentation conditions are therefore of primary interest, requiring additional bathymetry data.

In the estuary, the navigational channel is the predominant flow channel, but is only one of the many channels that support flow Detailed bathymetry covering the entire estuary, including the sand shoals and the periphery of the small island, would be required for hydrodynamic simulation of the estuarine tidal circulation These data are available through the bathymetric atlas of the Columbia River estuary (CREDDP 1983), and from COE surveys of the estuary

3.2 TIDES

Tidal data is an important forcing parameter for a tidally influenced river such as the lower Columbia River The mouth of the river forms an open water boundary, so free surface elevations as a function of time are required as boundary conditions for forcing the tidal circulation in the estuary Irrespective of the model type, water surface elevations at the boundaries of the model domain are required; e g , the estuary mouth and any chosen upstream boundary USGS and COE have many years of continuous measurements at various locations including Warrendale, Portland (Willamette River), Astoria, Vancouver, and Longview. In addition, tides can be predicted along the river using models developed to assist Columbia River shipping (Beeman 1985). Tidal data necessary for modeling purposes are available.

3.3 FLOW FROM BONNEVILLE DAM AND MAJOR TRIBUTARIES

Accurate flow releases from Bonneville Dam are available on an hourly basis from COE within their CROMS database system Mean daily flows are available for major tributaries such as the Willamette and Sandy Rivers in Oregon, and the Washougal, Kalama, Lewis and Cowlitz Rivers in Washington, through the USGS WHATSTORE database These data are sufficient for running one-dimensional flow models in the upper river However application of two dimensional models is recommended in the intermediate region (RM-37 to RM-54), and also other locations in the upper river where multiple channels and mid-channel islands exist. The hydrodynamic models are used to predict the water particle velocities, and require current meter records for verification

A major data gap is identified regarding flow meter data on the river There are limited USGS tide stations on the main Columbia River and only some of them include current meter records Considering the long length of river from RM-146 at the Dam to RM-37 at Tenasillahe Island, additional current stations are required to obtain sufficient spatial distribution for verification of two-dimensional hydrodynamic models

There is insufficient current meter data measured from bank to bank in the Columbia River at flow bifurcations and locations immediately upstream and downstream of the mouths of the tributary waterways Cross section flow velocities measured during high discharge and a low discharge events in the Columbia River (greater than 300,000 cfs and lower than 150,000 cfs measured at the Dalles) are needed These measurements should be bank to bank, and positioned upstream and downstream of tributary mouths such as the Sandy, Willamette, Lewis and Cowlitz Rivers. These measurements should also be taken at reaches of the river where multiple channels exist The bank to bank measurements should be measured simultaneously both in the main stem and the secondary channels to identify the flow split through these river reaches for purpose of model verification Examples of these multiple channel reaches include the Cathlamet channel, Wallace Slough, Bradbury Slough, Fisher Island Slough, Lord Island Slough, Carrols Channel, Martin Slough, Oregon Slough and Multnomah Channel

On the other hand, current meter records have been collected at several locations in the estuary, and at several depths The National Oceanic Survey field program conducted in 1981 and the CREDDP field study program conducted in 1980 are excellent sources of current and tidal data These data will be valuable for the verification of a three-dimensional model in the estuary It is anticipated that limited current data, if any, will be required for the estuary

3.4 SEDIMENT TRANSPORT AND DREDGING RECORDS

Sediment transport data is required to verify a model subject to sediment budget and sediment movement The principal data required is grain size distribution, sediment density and physical characteristics, and quantitative estimates of the sources and sinks of sediments. Sediment data on grain size and other sediment physical characteristics are available mostly from dredging records of COE (1980, 1991) This information is required for running the sediment transport model and predicting sediment quantities moved by the river flow. While sediment characteristic data are available, the field data on site-specific sediment transport measurements, which are required for model verifications, are limited Sediment transport measurements exist near Vancouver and are available from USGS, and COE records near Sauvie and Puget Islands (COE 1986 and 1988, respectively)

The available sediment characteristic data are primarily from the navigational channel These data are predominantly for sand-sediment deposition The majority of depositional areas for fine-grain, silt-sized sediment are located in the backwaters and sloughs where sediment data are lacking The available data and studies allow a basis for qualified estimates of fluvial bedload supply in and out of specific river reaches A specific study to measure bedload from the river into the estuary has not been conducted Measurements of suspended loads have been conducted using turbidimeters in the estuary, but not in the upper river. For sediment transport verification, data are needed on actual sand or suspended sediment transport, measured across several transects as a function of time and location on the river There is lack of sufficient bedload and suspended load data to verify sediment models for the entire reach of the Columbia River. The data should be measured by appropriate field sampling from bank to bank during varied discharge conditions These samples should be obtained from two transects positioned upstream and downstream of tributary mouths and at another four to six selected locations along the river.

3.5 SALINITY - TEMPERATURE DATA

Salinity data are required primarily for the purpose of modeling the estuarine processes that are influenced by salinity stratification This information has been developed through the COE physical model study and the CREDDP report on circulatory processes by Jay (1984)

3.6 SUMMARY - DATA AVAILABILITY

In conclusion, relatively good data availability exists in the estuary, primarily as a result of the CREDDP efforts Three large data gaps have been identified

1 Lack of sufficient current meter data or flow data on the Columbia River main stem at several locations above the estuary where the flow bifurcates around the mid channel islands and near the mouths of various tributaries.

2 Lack of sufficient sediment bed load and suspended load data as time histories over the entire river upstream of the estuary

3 Lack of sediment characterization in secondary channels and backwater areas in the river upstream of the estuary

A minimum database required for the development of simple hydrodynamic and sediment transport models is available but has not been compiled Data availability and gaps related to contaminant transport are addressed in the Task 2 reports on pollutant characterization (Tetra Tech 1992a)

4.0 CONCLUSIONS AND RECOMMENDATIONS

Through a review of the physical characteristics of the lower Columbia River and the evaluation of the conceptual and numerical models available, the following conclusions and recommendations can be made

Hydraulic, Hydrologic, Sediment Transport, and Geomorphic Characteristics

1 Two distinct hydrodynamic zones can be identified The river system from RM-0 to RM-37 is the estuary region This region shows the influence of tidal flows, salt intrusion and the presence of tidal and residual circulation patterns which typify three-dimensional variations The estuary is also the sink or deposition zone for most of the sediments transported from the upper river

2 The second zone is the remaining stretch of the river from RM-37 to RM-146 The river demonstrates consistent dynamic open-channel unidirectional flow The channel bed slope is small and the flow is forced by discharges from the upstream tributary inflows and the releases from the Bonneville Dam. The region between RM-37 to RM-54 can be considered as a region of transition between the estuary and the riverine region because of flow reversals of significance during low river discharge

3 The Columbia River drains about 258,000 square miles of terrain Average discharge is about 260,000 cfs, varying from a low of about 100,000 cfs in the months of August - November to a regulated high of about 500,000 cfs in the months of April - July The influence of tides can be measured upstream to the Bonneville Dam The duration and locations of flow reversals depend upon river discharge and tidal amplitudes Flow reversals as far upstream as RM-95 have been noted, but as more typical below RM-75 The influence of salinity intrusion can be felt up to RM 27 during low flows and neap tides

4 Columbia River flows transport large volumes of sediments as suspended load and bed load The sediment transported in suspension is estimated at 10 million tons/yr, and the sediment transported as bed load is estimated at about 1 to 2 million tons/yr. About 35 percent of sediments entering the estuary is deposited within the estuary and the rest is transported out of the river mouth into the Pacific Ocean Maintenance of navigational channels is a major concern, requiring a reported average of 8,000,000 cubic yards of sand (10 5 million tons, assuming a uniform density of sand as 2 63 gm/cc and a volume fraction of 0 65) to be dredged from the Columbia River annually for this purpose

5 Pollutants enter the river through outfalls of domestic and industrial wastes and from sewage and storm water runoffs While dissolved contaminants are transported with the river flow, some contaminants attach to suspended and settleable sediments and are transported downstream via sediment transport Overall quality of the river is considered good. Generally, dissolved solid concentrations are less than 175 mg/L, water hardness is between 40 to 100 mg/L, and the suspended sediment concentration in the water column is low, about 20 to 200 mg/L

Numerical Modeling of The Lower Columbia River:

1 Numerical modeling of the lower Columbia River involves three major components: 1) a flow model that is driven by the tidal and river free surface elevation, slopes and upstream flow, 2) a sediment transport model, and 3) a contaminant transport model The flow model provides the necessary input, namely fluid particle velocity as a function of time and space, to the sediment and contaminant transport models The transport models then predict the concentration of pollutants and sediments with respect to time and downstream distance Based on geomorphic complexity and modeling considerations, the river has been divided into 1) estuary region, 2) intermediate region, and 3) riverine region

2 For performing numerical simulations with reasonable accuracy, a three-dimensional model in the estuary, a two-dimensional model in the intermediate region, and a one-dimensional branched model with two-dimensional modeling for site-specific reaches in the riverine region is recommended

A number of models with different levels of sophistication exist Considering the computational costs and degree of sophistication required, a two-case approach for numerical modeling is recommended for consideration

4.1 CASE 1. CONSERVATIVE APPROACH

The conservative approach is used where results of the modeling study are required in a relatively short time frame with limited resources It is recommended that models that have already been used on the Columbia River be used These models have already been verified and are reliable The following models are proposed for application to the Lower Columbia River:

1 Estuary Region - Hamilton's Model (1984)

2 Intermediate Region - TABS-2 (Thomas & McAnally 1985)

3 River Channel Flow Region - Callaway's Model (Callaway et al 1970)
Site Specific Application- TABS 2 model

4.2 CASE 2. STATE OF THE ART APPROACH

If the ultimate goal of the study is to obtain the best possible simulation and if resources exist for data collection and verification of an untested model on the lower Columbia River, then this approach can be followed:

1 Estuary Region - CH3D (Sheng 1986)

2 Intermediate Region - TABS-2 (Thomas & McAnally 1985)

3 River Channel Flow Region - SEDICOUP (Holly & Rahuel 1991) Site Specific Application- TABS 2 model

The models recommended in the above two sections primarily address the flow simulation Most of them carry their own subroutines for simulations of sediment or contaminant transport Suitable transport models will have to be selected (Tetra Tech, 1992b) and coupled to these flow models, depending on the modeling study requirements

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6.0 GLOSSARY

The following terms, descriptions, and definitions will be used throughout the duration of the report They are intended to be descriptive, intuitive, and applicable to the Columbia River rather than exacting and technical.

Adsorbtion	Penetration of a liquid into a bulk of a solid
Adsorption:	Surface retention of (pollutants) molecules, atoms, or ions
Advection	The process of transport of water or of an aqueous property solely by the mass motion of water body, most typically via horizontal currents
Alluvial	Formed by the action of running water
Back Water	Connected lagoons or creeks parallel to a coast
Bathymetry	Science of measuring ocean depths in order to determine sea floor topography
Bed Load	Particles of sand soil or gravel carried by natural flow or stream, on or immediately above the bed
Bed Form:	A macroscale feature (much larger that the bed sediments) that is developed by bed load transport and deposition In the Columbia River, dune beds (analogous to wind-created sand dunes) is the dominant bed form
Calibration	Process of adjusting the parameters of a predictive model or instrument by comparison to measurements, to obtain correct readings
Circulation	Flow or motion of a fluid in or through a given area or volume.
Cohesive·	With tendency to hold together due to intermolecular attraction
Coriolis Force	Deflective force caused by the rotation of the earth on a body moving on its surface The magnitude of the force is proportional to velocity and mass of the body
Diffusion.	Spontaneous scattering and mixing of particles of a fluid

Discharge Velocity	Equals the flow of the river divided by the cross-sectional area Discharge Velocity usually increases with increased flow The velocity of the river varies across the river and with depth
Discharge:	The flow rate of a fluid at a given instant expressed as volume per unit of time
Dispersion	Equivalent of turbulent diffusion
Diurnal.	Having a period of cycle of approximately 1 tidal day
Dredging	Removing solid matter from the bed of a water area, typically for deepening channels, building canals, and constructing levees
Ebb Tide	Period of the tidal cycle associated with the decreasing height of a tide and outgoing flow in a tidal inlet
Effluent	The liquid waste of sewage and industrial processing
Flood Tide	Period of the tidal cycle associated with the increasing height of a tide and flow entering an estuary
Flow Structure:	Distribution of flow velocities as a function of location and time.
Fluvial.	Pertaining to or produced by action of stream
Friction Coefficient	An empirical coefficient that describes the resistance of the river bed to the inertial forces of river flow. The coefficient is based on river features such as bed grain size, larger river features such as mid-channel bars and bed forms, and vegetation within the wetted perimeter Generally, large rivers with small grain sizes (less than gravel size) in the river bed, such as the Columbia River will have a lower resistance to flow (and lower friction coefficient) than smaller rivers with coarse grains
Geomorphic (Characteristics)	Characteristics of change in surface features related to erosion.
Gradient:	Slope
Hydraulic (Characteristics)	Characteristics of the motion of water and its interaction with the boundaries.
Hydrodynamics:	Study of motion of a fluid and of the interaction of the fluid with its boundaries
Hydrology.	Science that treats the occurrence, circulation, distribution, and properties of waters of earth and their reaction with the environment

Laminar (Flow)	In laminar flow, fluid particles move along straight, parallel paths in layers or laminar The magnitudes of the velocities of adjacent laminar are not same and are governed by viscous shearstress Turbulence is not dominant
Meteorological	Pertaining to weather
Mid-Channel Island	A river island that has a significant portion of river flow on each side As the river flow splits, flow directions become much more complex Puget Island is a good example of a mid-channel island
One Dimensional Model	Model which assumes uniformity in vertical and lateral directions, and solves the equations of motion and transport along one x-coordinate (the direction of flow)
Open Channel	Any natural or artificial, covered, or uncovered conduit in which liquid (usually water) flows with its top surface bounded by the atmosphere
Physical Model	A scale model constructed based on laws of similitude to reproduce river flows in the laboratory
Precipitation	Equals the sum of rain and snow fall for a given duration of time There is wide variability in the amount and form of precipitation in the Columbia Basin. East of the Cascade Mountain has low precipitation which is largely snowfall and west of the Cascade Mountains has abundant precipitation and is dominantly rainfall This variability in precipitation results in unique runoff in the Columbia Basin (see definitions below)
Refraction	Change in direction of propagation of a wave associated with change in velocity of propagation caused by passage of the wave from one region to another
Salinity	Total quantity of dissolved salts measured in parts per thousand.
Salt-Water Wedge	A wedge shaped intrusion of salty ocean water into a freshwater estuary or tidal river It slopes downward in the upstream direction and salinity increases with depth
Semidiurnal	Having a period of cycle of approximately half a tidal day
Shoals	A submerged elevation rising from the bed of a shallow body of water and consisting of or covered by unconsolidated material and may be exposed at low water

Side-Channel Island	A river island, located near the bank of the river The significant river flow is only found in the main channel and the side channel has sluggish flow Sauvie Island is a good example of a mid-channel island
Slough	A minor marshland or tidal waterway which usually connects to other tidal areas, often more or less equivalent to a bayou
Stratification	Variation of density in the water column
Suspended Load	Solid particles that are carried by a stream in suspension for a long time
Three Dimensional Model	Mathematical model that solves the equations of motion and transport considering variations in vertical as well as horizontal directions in the x-y and z planes
Tidal Forcing	Periodic ebb and flood tidal motion induced by the gravitational forces causing circulation in the estuary
Tidal Flow Reversals	Change in the direction of river flow from downstream to an upstream flow caused by the action of incoming flood tide
Transect.	Cut transversely
Tributary Basin:	Consists of a lessor river and its associated watershed. Tributary basins in the lower Columbia River include such rivers as the Cowlitz, Willamette, and Sandy Rivers The tributary basin consists of all areas that contribute precipitation runoff and streamflow to the main tributary river
Turbidimeter:	An instrument that measures the turbidity of water
Two Dimensional Model	Model which assumes uniformity in the vertical direction and solves equations of motion in the lateral x-y plane, or a model which assumes uniformity in y direction perpendicular to flow, and solves equations of motion in x-z vertical plane