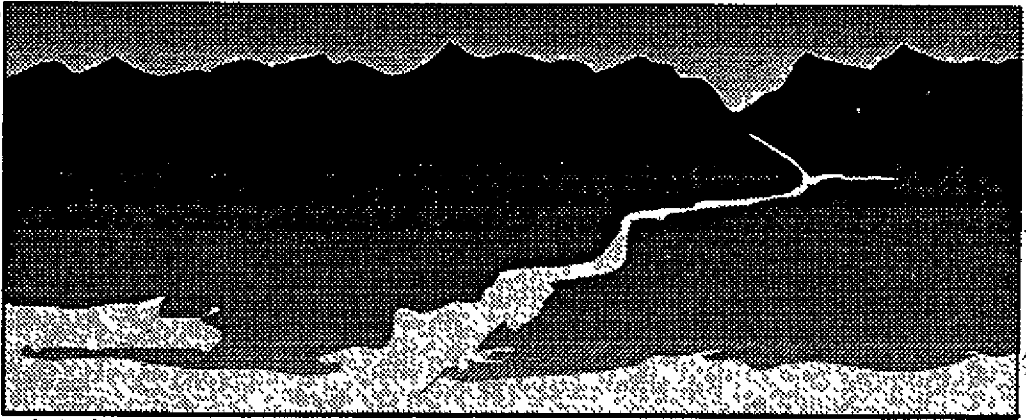
TC-8526-03
FINAL REPORT

LOWER COLUMBIA RIVER



BI-STATE PROGRAM

RECONNAISSANCE SURVEY OF THE LOWER COLUMBIA RIVER

TASK 3: REVIEW OF HYDRAULIC, HYDROLOGIC, SEDIMENT TRANSPORT, AND GEOMORPHIC CHARACTERISTICS OF THE LOWER COLUMBIA RIVER

MARCH 1992

Prepared By:
TETRA TECH
In Association With:
HARTMAN & ASSOCIATES

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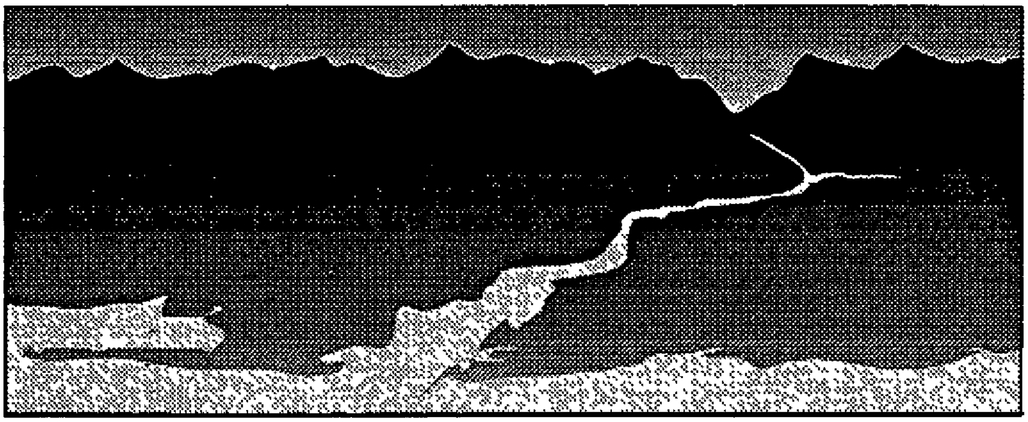

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MARCH 1992

Prepared For:

The Lower Columbia River
Bi-State Water Quality Program

Prepared By:

TETRA TECH

In Association With:
HARTMAN & ASSOCIATES

CONTENTS

APPENDICES

ABBREVIATIONS

RM	River Mile
COE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WA	Washington
OR	Oregon
LCRS	Lower Columbia River System
PGE	Portland General Electric

1.0 INTRODUCTION

The Lower Columbia Bi-State Water Quality Program (Bi-State Program) has been established to assess the ecological health of the lower Columbia River system from Bonneville Dam to the mouth of the river. The primary goal of the first-year of the program is to conduct a reconnaissance survey of the river to provide an initial assessment of the river's health. The objective of Task 3 of the first year's technical studies is to characterize the physical and hydrologic characteristics of the lower Columbia River. Three reports specified for the task aim to:

- Identify and review the physical characteristics of the river
- Develop a conceptual model of the river and make recommendations for numerical modeling of the river system
- Summarize the findings of the characterization and modeling reports and make recommendations for future studies to close data gaps.

This document is the first of the three reports required for this task.

The objective of the present report is to identify and review the hydraulic, hydrologic, sediment transport, and geomorphic characteristics (jointly termed physical characteristics) of the river. Understanding these characteristics is essential to understanding the transport processes and fate of contaminants in the river system. The information summarized in this document will be combined with the development of a conceptual model in a subsequent report to assist in making recommendations for numerical models for determining the fate of contaminants in the lower Columbia River. Information gathered for this report has also been used in designing the field reconnaissance survey (Task 6), carried out in Fall 1991. Selection of water, sediment, tissue, and benthic sampling stations for this survey depends on understanding the physical characteristics and processes that transport contaminants from local sources and, ultimately, affect the health of the entire river.

A further objective of this report is to make recommendations for segmenting the river into discrete reaches by identifiable physical characteristics. Segmenting the river in this manner will facilitate a recommendation on modeling of the physical processes responsible for transport of contaminants. The river segments will be selected in conjunction with the ecological zone recommendations of Task 4.

The report first reviews the available literature on the physical characteristics of the lower Columbia River. The literature review should be considered representative and not comprehensive. Other relevant information is available in gray literature of government agencies and private sources. Sources and locations of data and information have been identified to provide a basis for further study during development of the conceptual model, recommendations for numerical model(s), and subsequent implementation of a selected model. A more complete review of literature is included in the Task 1 Reports, *List of Material to Evaluate*, and *Review of Existing Data and Preliminary Identification of Problem Areas and Data Gaps*.

The next section of this report is a discussion of the hydraulic, hydrologic, sediment transport, and geomorphic characteristics of the lower Columbia River. Based on the physical characteristics of the river and best professional judgement, recommendations are made for segmentation of the river.

The report concludes with a summary of the primary findings in the report, an identification of gaps in the existing physical data, and recommendations for further studies to fill the data gaps.

2.0 LITERATURE REVIEW

Literature on the physical characteristics of the lower Columbia River has been reviewed in conjunction with Task 1, Initial Data Review and Synthesis. This review has been used as a basis from which to build a more discipline-specific compendium of information. The review has been conducted to analyze the strengths and weaknesses of existing data and to develop a database from which to make informed decisions on physical segmentation of the river and the selection of sampling locations.

This review focuses on scientific and engineering studies including both theoretical and field investigations addressing the hydraulic, hydrologic, sediment transport, and geomorphic characteristics of the estuary and riverine portions of the lower Columbia River. Existing models for the river are briefly discussed. While there are a number of studies and reports available, the surveys, data samplings, and sites investigated are not uniformly distributed from Bonneville Dam to the river mouth.

From 1912 through the early 1970s, a series of multi-purpose dams were constructed on the Columbia River and its major tributaries. These dams significantly affected river flow structure, sediment transport, and bathymetry. Deepening the navigation channel by dredging, constructing flow training devices, and stabilizing the bank further affected localized current velocities and sediment transport in the river downstream of the dams. These significant alterations in the hydrodynamics of the river have been ongoing since 1939. The major dam construction and the existing 40-foot deep-draft navigation project were essentially completed in the early 1970s. But significant man-made alterations to the lower Columbia River system have been limited since 1970. Because of this, the data and studies conducted after 1970 are considered most relevant (McConnell 1990), and have been considered for this study.

The primary sources of information evaluated here are reports from 1) the Columbia River Estuary Data Development Program (CREDDP); 2) U.S. Army Corps of Engineers Portland District (COE); 3) U.S. Geological Survey (USGS); and 4) university, private, and non-federal government agency research programs. The CREDDP reports primarily address estuarine processes of the lower Columbia River from about river mile (RM) 46 downstream to the river mouth. COE reports include information on dredging of navigation channels, water storage, bed and suspended sediments, sediment transport, and flow data related to river regulation Most of the USGS sources provide information on sediment transport of the river and hydrology of the river basin. The university, private, and non-federal government agency research reports include a wide range of site-specific, topic-specific, and interdisciplinary information selectively considered for relevance to the Bi-State Program.

Scientific and engineering investigations have focused on specific river reaches based on fundamental ecological issues, population centers, and/or industrial and shipping centers Geographically, the most densely studied areas of the river include 1) the estuary (RM 0-37), and 2) the riverine portion, focusing on the Longview-Kelso area (RM 60-70), and the Portland-Vancouver area (RM 105-115).

2.1 CREDDP AND OTHER ESTUARINE STUDIES

Most of the literature reviewed has focused on the estuarine portion of the river from the Pacific Ocean upstream to RM 37. This section of the river includes the City of Astoria (an important population and shipping center), deep draft and shallow draft navigation area, commercial and recreational fisheries, and extensive areas designated as wildlife refuge (Lewis & Clark National Wildlife Refuge; Julia Butler Hanson Natural Wildlife Refuge). In spite of its expanse and large area (relative to channel conditions upstream), the estuary is the most densely studied reach of the river.

Large volumes of data and studies are documented in the reports of CREDDP. These studies provide the most comprehensive scientific data on the lower Columbia River, although they are limited in 1) areal extent, 2) spatial and temporal data, and 3) data on the effects of the Mt. St. Helens eruption. Much of the data is available through reports, such as the *Characterization of Water Quality V-II,* (CREDDP 1980). This report contains pure data on the estuary region, particularly with regard to salinity, temperature, suspended particles, particulate trace metals, and radioactivity.

For most hydrodynamic flow responses, the bathymetry of the flow region is very important. For example, circulation and sediment transport are influenced by the elevation of the river bed and bed sediment. CREDDP published a bathymetry atlas of the Columbia River estuary in 1983. Other maps and atlases are also available, such as the *Atlas of Physical and Biological Characteristics* (CREDDP 1984). The COE conducts annual bathymetric surveys of the navigation channel. These surveys cover the estuary thalweg, or main thread of channel flow, providing a 3,000- to 5,000-foot-wide bathymetric record from the estuary mouth upstream to RM 34 The same surveys provide a bank-to-bank bathymetry for RM 34 upstream to Bonneville Dam.

Several sources are general guides to the physical characteristics of the river estuary. Abstracts of major CREDDP publications (CREDDP 1984) is a guide to CREDDP literature. A synopsis of the hydrodynamics of the estuary is presented in Simenstad (1984), which discusses river hydrology, sediment supply, circulatory processes, and tidal processes. Jay (1984) addresses the issue of tide-induced circulation in the presence of river flow in the estuary. Theory of estuarine circulation, tidal processes, system energetics, salinity distribution, salt transport, and low frequency flow processes are analyzed in this report. This report also is recommended by Hamilton (1984) for use in numerical modeling. The sediment transport mechanisms of the estuary are presented by Sherwood et al. (1984). These and other studies were later published in *Progress in Oceanography* (Angel and Smith 1990).

Other relevant estuary studies were conducted in the 1970s. Mistiano (1974) collected data on water temperature, salinity and zooplankton from several stations in the estuary. Hubbell and Glenn (1973) examined sediment size and radionuclide concentrations in several areas along the river and attempted to quantify the sediment transport mechanisms influencing the estuary.

2.2 RIVERINE STUDIES

Reaches of the river in the Longview-Kelso area have been extensively studied due to the area's importance as an industrial, shipping, and population center. Industrial and municipal contaminants enter the river by various pathways along this river reach. The Cowlitz River, the second largest tributary below the Bonneville Dam, enters the Columbia River at Longview and has been a major source of sediment since the eruption of Mt. St. Helens in 1980. Large-scale dredging operations have been required to clear and maintain the COE navigation project depth of 40 ft since the eruption. Continued dredging of the Mt. St. Helens sediment introduced into the Columbia River is gradually being reduced as the restabilization of the Cowlitz and Toutle river systems are completed.

The river reach between Longview and the Trojan Nuclear Plant (RM 60-72) has been the subject of numerous studies to monitor the effects of the Portland General Electric (PGE) nuclear power plant outfall and outfalls from the wood products industry. The PGE Trojan Nuclear Plant produces a thermal plume from cooling water effluent just upstream of the Cowlitz River at RM 72. Snyder and McConnell (1970) collected water temperature data at RM 72 for one year to evaluate the effect of impending power plant and industrial development on the river's ecology.

Another heavily studied reach of the river is the Portland-Vancouver area. This reach passes through the largest population center bordering the Columbia River and supports large industrial and shipping facilities. Industrial and municipal contaminant sources exist along both the Columbia and the Willamette rivers, the largest tributary below Bonneville Dam. A significant number of Superfund sites also lie along this reach of the river and may contribute to the contaminant load through groundwater flow or surface water runoff.

Rickert et al. (1977) conducted a survey of trace metal distributions from sediment samples taken from the Willamette River in 1973. The study examined the increased levels of trace metal concentrations from pulp and paper mills and urban runoff in the Willamette River, the largest tributary to the study area. Young (1989) assessed the water quality in the river near outfalls upstream of Portland, from RM 107 to RM 121. The James River Corporation also monitors water and sediment quality in the river near its pulp and paper mill at Camas, Washington (RM 121).

Scientific data are sparse from upstream of the greater Portland metropolitan area to Bonneville Dam. The USGS monitors water quality at Warrendale, Oregon (RM 140), and river surface elevations immediately downstream of Bonneville Dam (RM 146). Records of daily discharge flow release at The Dalles Dam are available from the USGS. Other studies have focused on radionuclide concentrations, often providing important information on the sediment transport characteristics of the river. From 1944 to 1971, nuclear reactor coolant water was discharged into the Columbia River at the Hanford Atomic Energy Reservation (RM 300). This radioactive coolant activated the naturally occurring stable elements in the river and formed radionuclides. These radionuclides concentrate in sediments and biota or remain in solution and have been distributed downstream. Haushild et al. (1973) examined the transport of radionuclides in the Columbia River from Pasco to Vancouver, Washington (RM 320 to RM 105) by time series analysis of particulate and dissolved concentrations of the 13 radionuclides studied. This study examined the hydrodynamic and sedimentation characteristics of the river system with respect to transport of radionuclides. The study showed that seasonal variation in concentration of each radionuclide depended on seasonal variations in the discharge. Haushild et al. (1975) studied the distribution of radionuclides by examining the bottom sediments from the Hanford Reservation (RM 300) to Longview (RM 70)

Other available studies have focused on water quality, while providing a good source of data and information related to the hydrodynamic behavior of the river Tetra Tech, Inc. (1976) performed a water quality analysis on the river from Pasco, Washington (RM 320) to Astoria, Oregon (RM 15). Flow data for the study were obtained through the STORET database and USGS publications.

A more general overview of conditions in both the estuary and riverine portions of the river is provided in other published reports. Hines et al. (1978) provides a good introduction to the physiographic setting of the Columbia River as well as an assessment of water quality conditions. Hydrologic and geomorphic conditions considered most important for controlling water quality are discussed. The study concludes that the overall water quality of the river was good at the time of the study. In high flow conditions, the dissolved solid concentration was less than 175 mg/L, hardness was between 40 and 100 mg/L (CaCO3), and the suspended sediment concentrations were low, about 20 to 200 mg/L The report addressed other dynamic aspects of the river including discharge rates, river bed channels, sediments, tides, and river free surface gradient as a function of distance along the river.

Numerous COE studies give information on the impacts of dredging on the water quality of the lower Columbia River, as well as data on hydraulics, sediment transport, and geomorphology. Most of these studies have been concerned with maintenance of navigational channels. A total of 8-9 million yd^3 of material is dredged from the Columbia River per year (Clairain et al. 1977; Eriksen, K., 21 July 1991, personal communication). The material is relatively clean sand, gravel, and shells.

One COE investigation (1979) studied the effects of disposal of Portland harbor-dredged material in the Willamette River by placing it in the river's main channel immediately upstream from where the Willamette enters the Columbia. The study demonstrated that finer grain bed sediments deposited in the main thalweg of the Willamette's main channel were successfully scoured and transported downstream during maximum flow conditions, while water quality was maintained. A similar study was completed by Weyerhaeuser in Longview (RM 64) (Hartman and Beeman 1987) and by the COE at Pillar Rock (RM 28) (Hartman 1981). Another study conducted by the Clarain et al. (1977) examined the disposal of the dredged material at Miller Sands Island (RM 205). Sediment samples, turbidity, and concentrations of settleable solids were also analyzed in that study.

In 1980, the eruption of Mt St. Helens caused a huge sand flow down the Toutle and Cowlitz rivers into the Columbia River, reducing the navigation channel depth from 40 ft to 15 ft. The Portland District COE immediately initiated work on restoration of the river depths (1985). Another study (COE 1989) presents sieve analysis of sediment samples taken from 1980 through 1988. Sampling stations were located from the mouth of the Columbia to Camas, RM 121. Columbia River bed sediment information has been organized into a computer database by the Portland District (COE 1980). This database, predominantly grain size distribution of grab samples collected from the river bed, has been augmented annually and is available for public review.

The USGS has published additional information on sediment characteristics and other hydrodynamic properties throughout the lower river. Fuhrer analyzed bottom sediment samples at stations along the river for several years (Fuhrer 1986, 1988, 1989, 1990). Water quality data, including the flow characteristics at various stations, are presented in other USGS reports (USGS 1984a,b; 1989; 1990a,b).

Other useful studies have been conducted by a variety of researchers. Hedges (1984) analyzed the distribution of organic sediments throughout the river system to the continental shelf. Ebel et al. (1989) present a holistic picture of the Columbia River, summarizing the morphometry, hydrology, flow regimes, sedimentation, and water quality.

2.3 NUMERICAL MODELING STUDIES

Most studies have focused on water quality evaluation and quantification of sediment transport. Detailed technical applications of numerical modeling, however, are limited. Callaway (1970) presents a mathematical model for the river from Bonneville Dam to the Pacific Ocean. It is a simplistic application using the finite difference method in the sense that flow is assumed to be fully mixed in each segment and occurring in simple channels. The model attempts to predict the dispersion of contaminants by the solution of diffusion equation in one dimension Models HEC-2 (used for water surface elevations and flood studies) and HEC-6 (for sediment transport and deposition modeling) were suggested for studying the Cowlitz and Columbia rivers after the Mt. St. Helens eruption (COE 1985) A good review of the modeling pertaining to the river is presented in Hamilton (1984). Hamilton simulates two-dimensional wind and tide forced flow in the Columbia River Estuary. This is a multiple-channel model that includes a channel connection scheme and provides for variable channel width and depth. The model reproduces the tidal and flow data and the analysis of Jay (1984) with reasonable accuracy.

A numerical, two-dimensional, finite element model was applied to evaluate potential impacts on current patterns and therefore sedimentation in a ship berthing area of the river near Longview (RM 64) (Ogden Beeman 1988). The numerical model used was the Finite Element Surface-Water Modeling System: Two Dimensional Flow in a Horizontal Plane (FESWMS-2DH), developed by the USGS for the Federal Highway Administration.

Models complementing the general flow and dispersion models are useful. One such model is SIMPT (simplified particle transport model), which simulates the accumulation of wash solids or particulate pollutants in many storm events. SIMPT was applied by the City of Portland Bureau of Environmental Services (1989) in the Columbia Slough Planning Study to determine the pollutant loading to the Columbia Slough from stormwater runoff.

3.0 THE HYDRAULIC, HYDROLOGIC, SEDIMENT TRANSPORT, AND GEOMORPHIC CHARACTERISTICS OF THE LOWER COLUMBIA RIVER

Studying the hydraulic, hydrologic, sediment transport and geomorphic characteristics of the lower Columbia River enables better understanding of the hydrodynamic behavior of the river. These interdependent characteristics give sufficient information to model the river system conceptually as well as numerically. However, the analysis of the entire river from Bonneville Dam to the river mouth is complicated by the presence of both a major river system and a large estuary with strong tidal influence.

Geomorphically, the riverine portion can easily be distinguished from the estuarine portion. The Columbia River widens from a width of about 2,100 ft at RM 53 into a broad estuary of about 47,000 ft in some transects. The sudden increase in the width and subsequent cross-sectional area reduces velocity. At the same time, the estuary also opens channel flow to periodic tidal forcing. As a result of channel widening and reduction in outward flow velocities, the river's capability to transport sediments is reduced in reaching the estuary. The estuary thus serves as a sink for a significant amount of sediment transported down stream.

Hydraulic conditions governing flow in the riverine section are primarily a function of gravitational potential energy, while in the estuary flow is governed by tides considered moderately strong relative to river discharge (Dyer 1973). Hydraulically, flow in riverine segments of the lower Columbia River can be described as an unsteady open channel flow. Flow in the estuary is more complex and is governed by estuary boundaries, thalweg, secondary submerged channels, sand shoals, incoming river discharge, and tide induced flow. To predict flows, fate of contaminants, and sediments, it is easier to analyze the flow in the estuary and river segments separately, and then connect the two segments with matching boundary conditions.

A qualification to the approach of separate analysis is that the tidal influence on water surface elevation can be identified as far upstream as Bonneville Dam, and flow reversals in the river caused by high tide and low river discharge have been noted as high as RM 95 (Eriksen, K., 21 July 1991, personal communication). Given these data, the riverine segment at low river discharge conditions is not strictly an open channel flow. However, during typical flows of about 300,000 ft^3/sec no flow reversals greater than one-hour duration would be expected upstream of RM 73 regardless of the tidal heights at Astoria (Snyder and McConnell 1973) This would represent a minor total flow reversal time of less than 0.01 percent during an average discharge year on the Columbia River. Thus, for simplifying the understanding of the river behavior, the importance of separate analysis for the riverine portion and the estuarine section is emphasized.

3.1 HYDROLOGIC CHARACTERISTICS

The hydrologic characteristics of a river system are determined largely by the river basin climate and geological nature and control structures constructed. Two hydrologic characteristics directly affect the hydrodynamic behavior of the lower Columbia River: 1) precipitation, and 2) tributary stream flows.

Precipitation is a climatic factor that establishes hydrologic features based on the amount and distribution in the river basin. To the hydrologist, precipitation is the general term for all forms of moisture emanating from the clouds and falling to the ground. Once on the ground, a part of the precipitated water makes its way via feeder streams and surface runoff to minor tributaries, which empty into major tributaries and then into main stem of the river.

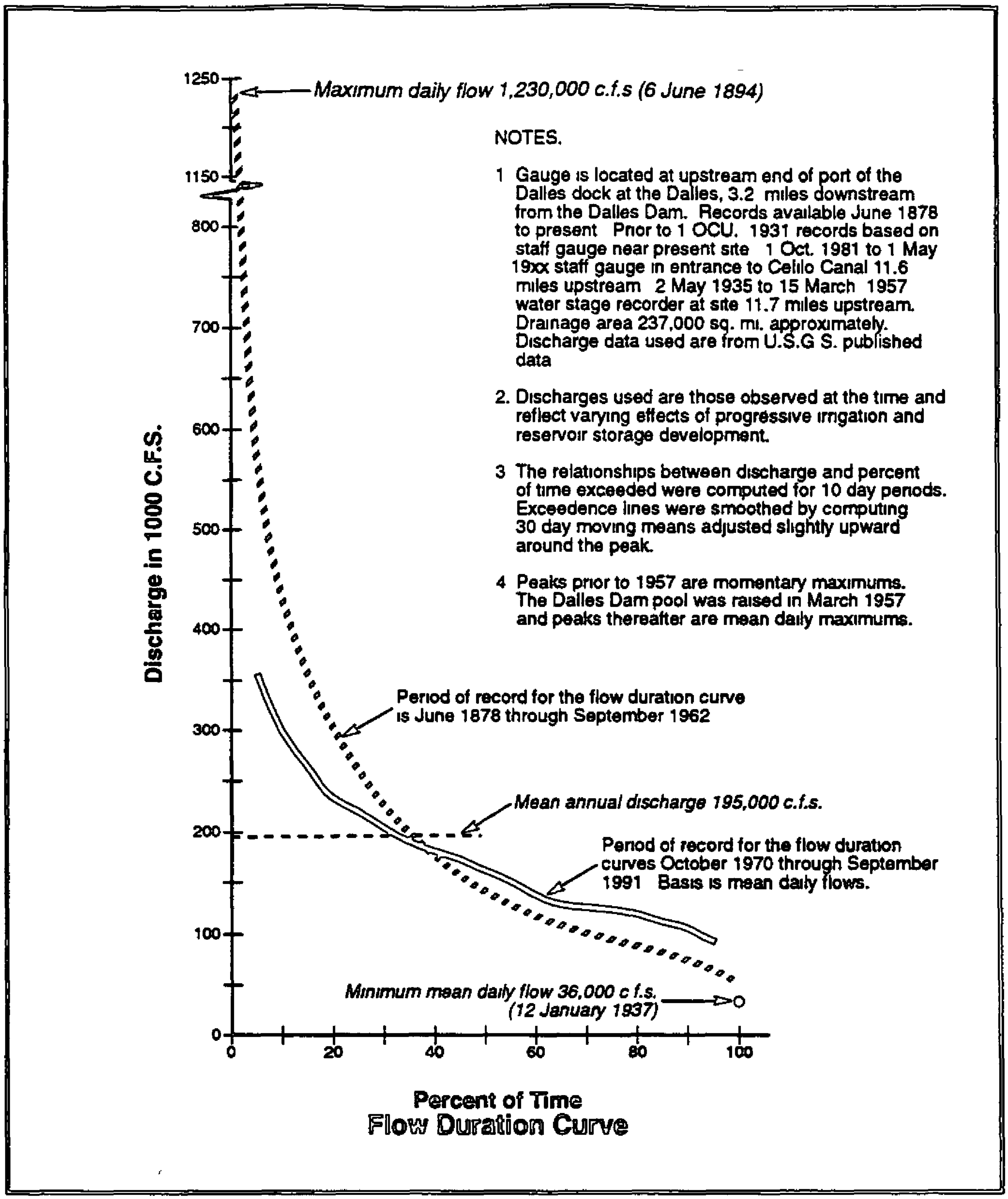
Net river discharge is directly related to the amount of rainfall or snowfall received within the drainage basin. Because rainfall, snowfall, and snow melt depend upon climate, seasonal variations of these three parameters can alter the discharge. Stream velocity (ft/sec) is an important characteristic of the river for all engineering activities and the water budget planning. The stream velocity in turn is controlled by the hydraulic characteristics of the river channel.

As discussed, the Columbia River—the largest U.S. river to empty into the Pacific Ocean—discharges about 260,000 ft^3/sec on an average (Simenstad et al. 1984). This mean annual discharge to the Pacific is approximately twice the amount of freshwater discharge from all other rivers in California, Oregon and Washington combined (Whetten 1969). The flow of the Columbia River is distinctly seasonal, with the region east of the Cascade Mountains receiving continental-type weather and significant snowfall and snow pack. Peak discharge in the lower Columbia River system occurs in May-June as a result of snow melt and freshet conditions in the interior drainage basins east and upstream of Bonneville Dam. The minimum discharge is normally in September, during late summer and early fall. The marine climate of the lower Columbia River west of the Cascade Mountains and tributary area downstream of Bonneville Dam is characteristically wet and foggy in winter and dry in summer. Nearly 25 percent of the total runoff water entering the river downstream of Bonneville Dam originates from west of the Cascades due to higher precipitation. The annual precipitation in this area, especially in the higher slopes, varies between 90 and 200 inches, while east of Cascades, precipitation varies widely but can be less than 8 inches annually. The following are the hydrological seasons of the lower Columbia River based on this seasonal variation:

- Winter (November-March, rainfall dominated, moderate to high discharge, fluctuating flow)
- Spring (April-June, snow melt dominated, highest flow)
- Summer (July-October, dry climate conditions with low flow) (Simenstad 1990).

3.1.1 Flow Regulation

Flow in the Columbia River is heavily regulated. The upper Columbia River, including tributaries, has 52 storage projects or dams with nearly 40 million acres (1.721×10^{12} ft^2 or 160,000 km^2) of storage capacity: about 35 percent of the annual flow (COE 1986). The major tributaries to the lower Columbia River—the Willamette, Cowlitz, and Lewis rivers—also have considerable flow regulation from other upstream storage projects. The storage projects regulate the flow for flood reduction, irrigation, power production, navigation, fish passage and other purposes. Storage projects affect flow by releasing water to augment flow during summer low periods and by storing water to reduce flood peaks during winter and spring. Pre- and post-1970 storage project flow duration is shown in Figure 1, which represents a pre- and post-regulated flow condition at The Dalles, Oregon upstream of Bonneville Dam. At The Dalles, the average annual discharge was reduced by 10 percent, while the peak flood discharge was reduced from more than 450,000 to 300,000 ft^3/sec due to diversion for irrigation and change in the climatic conditions (COE 1986).



Maximum daily flow 1,230,000 c.f.s (6 June 1894)

NOTES.

1 Gauge is located at upstream end of port of the Dalles dock at the Dalles, 3.2 miles downstream from the Dalles Dam. Records available June 1878 to present Prior to 1 Oct. 1931 records based on staff gauge near present site 1 Oct. 1981 to 1 May 19xx staff gauge in entrance to Celilo Canal 11.6 miles upstream 2 May 1935 to 15 March 1957 water stage recorder at site 11.7 miles upstream. Drainage area 237,000 sq. mi. approximately. Discharge data used are from U.S.G S. published data

2. Discharges used are those observed at the time and reflect varying effects of progressive irrigation and reservoir storage development.

3 The relationships between discharge and percent of time exceeded were computed for 10 day periods. Exceedence lines were smoothed by computing 30 day moving means adjusted slightly upward around the peak.

4 Peaks prior to 1957 are momentary maximums. The Dalles Dam pool was raised in March 1957 and peaks thereafter are mean daily maximums.

Period of record for the flow duration curve is June 1878 through September 1962

Mean annual discharge 195,000 c.f.s.

Period of record for the flow duration curves October 1970 through September 1991 Basis is mean daily flows.

Minimum mean daily flow 36,000 c f.s. (12 January 1937)

Flow Duration Curve

Figure 1. Flow -Duration Curves, Columbia River at The Dalles, Pre and Post 1960's Flow Characteristics

3.1.2 Tributaries

Major tributaries of the mainstream Columbia River upstream of Bonneville Dam are the Kootenai and Pend Oreille rivers in Canada; the Spokane, Okanogan, Wenatchee, Yakima, and Snake rivers in Washington; and the Umatilla, John Day, and Deschutes rivers in Oregon. These tributaries originate high in the mountains and their flow is a function hydrologically of the snow pack and ice melt of the continental-type climate, except for the Deschutes River, which is groundwater controlled with a stable discharge

In the river section from Bonneville Dam to the Pacific, the major tributaries and drainage basins are the Washougal, Lewis and Cowlitz rivers in Washington, and the Sandy and Willamette rivers in Oregon. These tributaries carry runoff water from the western, marine-type climate, and their flow is predominantly a function of Pacific storm fronts and high-intensity rainfall in the drainage basins.

3.1.3 Flow Conditions

During low river flows, stream width in the river varies significantly between the riverine and estuarine segments. The riverine segments upstream of Puget Island, RM 47, are relatively constant, ranging from 3,500 ft to 5,500 ft bank-to-bank during low flows The estuarine width changes significantly, from less than 4,000 ft at RM 37 at the upstream end of the estuary to about 47,000 ft at RM 23 (Cutshall and Johnson 1977).

In the lower Columbia River system, tidal influence can be measured at low river flows upstream to the Bonneville Dam. Although tides are moderately strong, the flow ratio of river discharge during a tidal cycle to the tidal prism is between 1 and 0.2, making the river current 10 to 50 percent of the tidal currents at the estuary mouth. Fresh water runoffs are an important hydrological parameter in such a situation where gradients are low and tides are asymmetrical (Ellis et al. 1977). Even at low river discharge, flow is strong enough to cause high slack water and low slack water to lead and lag, respectively, the tidal amplitude by about 25 minutes.

During low river flows of about 150,000 ft^3/sec and neap tides, salinity intrusion can extend up to Pillar Rock, RM 27, and during higher flows of about 300,000 ft^3/sec, salinity can extend up to RM 14 (Jay 1984). Surface-to-bottom salinity differences can exceed 20 parts per thousand. The lower estuary has a tendency toward salt-wedge type behavior, but strong tidal currents produce large vertical mixing. Salinity at the mouth can range from oceanic at high tide to zero at low tide when a salt wedge is completely advected out of the estuary (Jay and Smith 1990).

Time of passage through a particular river reach is an important parameter for characterizing the ability of a river to transport contaminants and sediments. Time of passage depends on the flow velocity. The time of passage identifies the speed at which pollutants move through a section of the river. Studies by Hines et al. (1978) show that the Columbia River flow, with a high discharge of 600,000 ft^3/sec during spring freshet, takes only 1 day to travel from RM 35 to RM 21 at the head of the estuary. The time of passage for a lower discharge of 100,000 ft^3/sec over this same distance is 4 days. The stream velocities calculated based on time of passage for mean tides will be lower during high tides and higher during low tides.

The similarity of flow conditions for the Columbia River at RM 128 to RM 130 has been compared using data from Beeman (Ogden Beeman et al. 1991). Given a discharge of 400,000 ft^3/sec during spring freshet, the Columbia River flow takes less than an hour (47 minutes) to travel the 2 river miles. The time of passage for a lower discharge of 100,000 ft^3/sec over this same distance is estimated at 2 hours. Although the tidal effect on river stage can be monitored at this reach, a high- or low-tide condition during low discharge would have negligible impact on the time of passage.

3.2 HYDRAULIC CHARACTERISTICS

Hydraulic characteristics of importance to this study include factors that deal with the conveyance of water in natural or artificial open channels. The flows in the lower Columbia River from Bonneville Dam to the estuary at RM 37 can be described by the principles of open channel hydraulics. There are several hydraulic parameters that control the direction, free surface elevation, and velocity of directional river flow: bed slopes, channel widths, hydraulic radius (dependent on channel cross section and wetted perimeter), and bed roughness. Because these parameters vary as a function of the individual reach and physical conditions along the river, the river's flow is nonuniform.

The Columbia River estuary is characterized by an unusual combination of large river discharge and strong tidal currents. For example, the flows and water movement in the estuary downstream of RM 37 must also be described by open channel hydraulics, but the complexity of the flow direction in the water column and the density of the liquid creates a more difficult analysis To further complicate analysis, most tidal exchange occurs through the North Channel of the estuary while the river flow mainly occurs through the South (navigational) Channel. Vertical flow structure is affected by the complex bathymetry consisting of many channels and shoals. Surface velocities during ebb tide often reach velocities of 5 knots (8.41 ft/sec) but upstream flow, especially along the bottom during flood, is not continuous and is often interrupted by pockets of downstream flow (Jay 1984). Upstream salt transport occurs mainly due to tidal mechanisms. Estuary behavior varies between a stratified salt wedge type to fully mixed.

3.2.1 Bed Slope

The average bed slope is low for the lower Columbia River downstream of Bonneville Dam. River classification based on channel bed slope allows comparison of river slope for various river systems (Table 1) (Mamak 1964). Columbia River Datum at Bonneville Dam (RM 146) is 11.27 ft above the mean lower low water (MLLW) at the river mouth. This leads to average bed slope of 0.001 percent for the river from RM 146 to the mouth, giving the lower Columbia River in the study reach a lowland river classification. Lowland rivers flow through extensive plains and usually have low banks. Their flows depend on the properties of the tributaries. These lowland waters tend to carry small grain or fine material, generally sand and silt as opposed to coarse sand and gravel.

Because the average bed slope for the lower Columbia River is very flat, either free surface slope of the water or hydraulic gradient tends to drive the river's flow velocity and direction. Free surface slope depends both on the inflow of water through the various tributaries and upper main stem of the river and on tidal inflow.

3.2.2 Bed Roughness

The friction coefficient parameter is a measure of the bed roughness, which opposes and limits the flow velocity. An empirical friction coefficient that has gained widespread acceptance is Manning's coefficient, "n," which relates the bed conditions of vegetation, grain size and bed form to the resistance to flow due to friction. The wide variation in the roughness coefficient value (n), together with the significant effect it has on flow calculations, places a premium on judgement and experience in selecting

TABLE 1. RIVER CLASSIFICATION BASED ON CHANNEL BED SLOPES	
Type	Slope
Mountain Streams	5%-0.2%
Upper Rivers	0.2%-0.1%
Middle Rivers	0.1%-0.05%
Lowland Rivers	Less than 0.05%

a proper value. It is necessary to test the n value against actual river stage and slope data to assure correct slope and coefficient assumptions.

Flow velocity depends directly on the values of the experimentally determined friction coefficient, the hydraulic radius, and the free surface slope. The mechanics of open channel flow are complex However, many open channel problems can be approximately solved based on a short-term assumption of steady flow. For short durations and isolated reaches of the river, the steady state values of Manning's n and hydraulic radius may be used with reasonable accuracy to determine flow velocities, river surface elevation, and flow direction.

3.2.3 Bed Forms

The lower Columbia River hydraulic characteristics such as stream velocity and direction, resistance to flow, and bed features are interrelated to the river's hydrology, geomorphology, and bed sediments. In most respects, hydraulics in the lower Columbia are similar to those of other sand-bedded streams. For example, the river downstream of Bonneville Dam to the mouth has sand wave bed forms typical of most sand bedded streams. However, the scale of these features on the Columbia River is large; sand wave bed forms measure as large as 20 ft from trough-to-crest (sand wave height) and 500 ft from crest-to-crest (sand wave length). The size of the sand wave bed forms vary with river discharge, increasing during maximum discharge and decreasing to a minimum size at low discharge (COE 1986).

Bed profile measurements taken at RM 72 and RM 57 during the low flow period in September showed a maximum height trough-to-crest of 13 to 14 ft and average sand wave lengths of 230 to 330 ft (Hartman, 1987). In the estuary, sidescan data collected by Sherwood and Craeger (1990) show large bed forms of heights up to 10 ft and wavelengths of more than 300 ft. Smaller forms were often found superimposed on the larger bed forms. A common feature of their sidescan record was a reflective, uneven and precipitous bottom indicating rock outcrops, boulder talus, and gravel banks.

3.2.4 Velocity

Because of the river's large-scale discharge and cross-sectional area values, and predominantly sand-size bed sediments, the river segment is considered to have a low resistance to flow and high flow velocities (approaching 8 ft/sec during high river stage) in the navigation channel (COE 1986). The average discharge velocity in backwater sloughs and lesser channels of the river may be less than 1/10 that of the navigation channel (COE 1986).

The river's velocity at low flows is significantly less than that at high flows. Velocity also varies significantly with river mile location and tide height. During low river flow conditions, daily current velocities for low-high tide conditions may range from 2-6 ft/sec downstream and 1-8 ft/sec downstream at RM 36 and RM 46, respectively (COE 1986). In addition, flow direction may be reversed in the water column between the surface and the bed at extreme high tide and low flow conditions.

3.2.5 Estuarine Tidal Circulation

Tidal circulation in the estuary is three dimensional. The significant vertical structure in flow depends highly on stratification, bottom friction, and bathymetry. This vertical structure may be explained using principles of mass conservation, which require that total ebb flow through any cross section be equal to the total river discharge plus the total flood flow and a stokes drift correction. The ebb flow is strongly sheared and the flood is uniform as a result; the net mean flow is inwards near the bottom in the lower estuary. In the upper estuary, salinity is absent during the ebb, and mean flow is outwards at all depths. The flood flow exhibits a maximum at the pycnocline. The lateral current variation is mainly due to bathymetry. The navigational channel supports the main river flow and the velocity is highest in the channel. However, the tidal ebb and flood flow takes place over a larger area that includes the North Channel and other subchannels. The islands and shoals force the currents around them resulting in the river's lateral flow structure (Jay 1984).

3.3 SEDIMENT TRANSPORT

Sediment transport is the movement, deposition and resuspension of sediment by river flow. A river is not only a flow of water, but is also a flow of sediment from upstream sources. In theory, the sediment load capacity of a river tends to be satisfied. If transport capacity exceeds the supply, or availability of sediment, scour will occur until a stabilized condition results. If supply exceeds capacity, shoaling will occur until a stabilized condition is created

Sediment transport is governed by channel hydraulics, flow energy, sediment availability, sediment grain size, and chemical reactions that control coagulation and sedimentation. The energy responsible for sediment transport depends upon flow velocity, which in turn depends on the discharge and the hydraulic parameters of the river reach. Depending on the intensity of the flow and sediment grain size, particles may be transported either as suspended sediment load or as bed load. The size of most of the sediment in the estuary is such that it is transmitted intermittently as suspended sediment under high tidal currents but moves regularly as bed load (Sherwood et al. 1984). The grains transported are generally finer than 0.5 mm in diameter. The mean size of the estuary sediment is 0.17 mm (2.5 phi) (Sherwood and Craeger 1990).

The Columbia River has a tremendous capacity to transport silt and clay, but the supply of fine sediments to the river system is limited. The region of interest, the river below Bonneville Dam, has been studied by the USGS (Hubbell and Glenn 1973; Haushild et al. 1975). Close to the Bonneville Dam (RM 146 to RM 138), the stream bed is mostly gravel and basaltic rock. Due to the high energy flow close to the dam, any material smaller than gravel (4 76 mm) is transported downstream. The bed material of the lower Columbia River through the estuary to the mouth is composed predominantly of sand with grain size from 0.1 to 0.5 mm (Hines et al. 1978). The bed sediment is identified as a fine sand with some gravel and minor amounts of silt and clay. Isolated areas of fine-grain silt and clay sediment with grain size less than 0.1 mm can be found in backwater and low energy flow locations.

Flow direction and magnitude (which controls the transport and deposition of the sediments) are controlled by the complex morphology of the river. Many times the flow is directed towards the banks and mid-channel islands, resulting in sizable erosion. The analysis of flow impacts on sediment transport is further complicated by the presence of eddies, tidal influence, and the existence of engineering structures like jetties, groins, revetments and other flow training devices.

3.3.1 Suspended Load

Suspended sediment load is that fraction of the total sediment load transported in the water column above the river bed. Suspended sediment transport is responsible for most of the sediment carried down to the estuary and onto the coastal shelf. Suspended sediments in the river were measured during CREDDP studies by Gelfenbaum (1983) and Sherwood (1984). Their studies show that most of the suspended sediment is of lithogenous type, with 1-10 percent organic content, and a modal grain size of 0.01 mm near the bottom. Higher up in the water column, the suspended material is fine silt and clay of grain size 0.001 mm. They noted that the effect of tidal circulation induces resuspension of coarser grains. The sediment concentration in the upriver portion of RM-50 is between 40 to 100 mg/L. The suspended concentration is much higher in the central part of the estuary, reaching 600 mg/L near Tongue Point. The suspended sediments slowly settle out of the water column when they enter protected or backwater areas.

The total suspended load of the Columbia River upstream of the Willamette River before construction of the dams was estimated at 14 million tons/yr Approximately 10 percent additional suspended sediment (1 to 2 million tons/yr) was introduced into the Columbia River by the Willamette River before construction of dams in the Willamette River drainage. The total suspended load in the Columbia that is being delivered since dam construction is estimated at 7-10 million tons/yr (Sherwood and Craeger 1990), but the generally accepted value is 10 million tons/yr (Jay and Good 1978; Haushild 1966).

3.3.2 Bed Load

Bed load is that fraction of the total sediment load transported along and in contact with the river bed, either by rolling downstream, or by saltation where grains are scoured into the water column immediately above the bed and immediately settle back to the bed downstream. Sediments greater than 0.1 mm are transported by bedload. Depending on the flow conditions, the bedload transport might occur by way of sand wave formation and migration downstream or by saltation, where grains jump from point to point in discrete steps. Approximately 45 percent of the channel from Bonneville Dam to Vancouver, Washington is covered with sand wave formations (Whetten and Fullam 1967). The total bed load of the river transported into the estuary segment was estimated at 1 million to 2 million tons/yr, or 10 percent of the suspended sediment load (Whetten 1969; Ogden Beeman 1984; Sherwood and Craeger 1990). That estimate does not include the increased Mt. St. Helens contributions. Critical velocity conditions required to initiate bed load motion for sand sediment grain sizes is calculated to range from an average channel velocity of 0.7 to 1 ft/sec. This equates to a discharge rate of approximately 150,000 to 170,000 ft^3/sec. Discharge conditions less than this would not result in significant bedload transport.

3.3.3 Estuarine Sediment Dynamics

Estimates of sediment entering and leaving the estuary suggest that little, if any, sand and coarser sediment leaves the estuary, except during high river discharges approaching 500,000 ft^3/sec (COE 1986).

Hubbell and Glenn (1973), using radionuclide evidence, estimated 30 percent of the suspended load is trapped in the estuary, and Nittrouer (1978) estimated entrapment of suspended load to be 33 percent. Sherwood et. al (1984) evaluated the long-term bathymetric changes, shoaling patterns, and sediment budget. Their result suggests that 20 percent of fine sediment is retained in the estuary and is slightly lower than 30 percent estimated by Hubbell and Glenn (1973). Most of the coarser bedload material remains trapped in the estuary, causing the estuary to shoal at a rate of 0.5 cm/yr.

3.3.4 Geologic Factors

The nature and type of sediment transported by a river depends upon the geological characteristics of the basin that it drains. Approximately 258,000 mi^2 of terrain is drained by the Columbia River (Whetten et al. 1969). This terrain includes igneous, sedimentary, and metamorphic rocks, along with extensive alluvial and eolian surface deposits. Effects of the geological differences are noticeable in the sediments found along the channel length. The multi-purpose dams upstream of RM 140 act as a trap for interior basin sediments carried down the river. The sediments of the lower Columbia River below Bonneville Dam contain volcanic materials, while the upper reaches near the Snake River consist of plutonic and metamorphic rocks. The volcanic sediment is coarser and generally forms the bedload. The eruption of Mt. St. Helens caused considerable coarse and fine-grained sediments to be transported down into the Columbia River and estuary (COE 1985). The presence of rock fragments, glass mantle grains, and pumice in the estuary sediments demonstrates the importance of volcanic contributions to the existing lower river and estuarine sediments (Roy et al. 1982; Simenstad et al. 1984). Sources of sediments other than from the Columbia River above Bonneville Dam include local tributaries, shoreline erosion, and wind transport of surface sediments.

3.4 GEOMORPHIC CHARACTERISTICS

Geomorphology is the study of surficial features of the earth and the physical and chemical processes that affect landforms, while fluvial geomorphology is applied to morphology (and mechanics) of rivers and river systems. The idealized fluvial system is separated into three zones (Simons, Li and Associates 1982). The uppermost is the drainage basin, watershed, or sediment source area, Zone 1. Zone 2 is the transfer zone where, for a stable channel, input of sediment can equal output. Zone 3 is the sediment sink or area of deposition. The study area consists of a Zone 2 (riverine segment) and Zone 3 (estuarine segment).

Lower Columbia River geomorphic features, such as channel patterns and channel gradient, provide a method of establishing relative channel stability. Classification of channels is also useful to focus attention on the most important factors that determine river morphology and shape the characteristics of the river system.

Natural lowland rivers demonstrate two distinct channel patterns:

- ☐ The braided stream planform, where multiple channels and mid-channel islands exist
- ☐ Meandering stream planform, where the channel is predominantly a single channel with low to highly meandering alignment.

The braided or meandering condition is a function of channel slope and discharge. A braided stream will reflect a steep channel slope relative to mean annual or bankfull discharge conditions, while a meandering stream will be commensurate with gentler slope conditions. Studies completed by Leopold and Wolman (1957), Lane (1957), and others demonstrate the relationship between bankfull discharge or mean annual discharge and channel slope.

All rivers may be separated into two main groups depending on freedom to adjust shape and gradient: 1) bedrock and 2) alluvial channels. The Columbia River below Bonneville Dam is an alluvial channel. Alluvial channels can be further classified primarily according to type of sediment load as bedload, mixed load, and suspended sediment load channels. Above the estuary, the lower Columbia is a continuing series of channels and braided, meandering, and straight channels can be identified.

Based on the continuum theory of sediment transport during deposition and erosion, another major division of alluvial channels is possible. An excess of total load in the channel causes deposition, a deficiency causes erosion, and between the extremes lies stable channel conditions. No natural river, including the Columbia River, can be clearly classified as stable, eroding, or depositing. However, it is possible to identify individual river reaches as fitting into one of these three conditions, thereby improving the conceptual and numerical approach to understanding river flow and sedimentation, as well as development of a numerical model.

The morphology of the Columbia River has been radically affected by humans. Upstream dam construction projects have generally eliminated the yield of all but fine sediments to the lower river because of deposition within the flood control pools. This has generally resulted in the lower river banks being starved of sediment replenishment and, as a result, has probably increased downstream bank erosion (COE 1986). Two studies (Ogden Beeman 1985, 1991) have identified a gradual increase in channel depths from bed erosion approaching 2 ft (RM 50 and at RM 129) during the 1980s. The COE and Port of Portland dredge nearly 8 million yd^3 of sediment per year to maintain the authorized navigation channel (Eriksen, K., 21 July 1991, personal communication). A significant volume of these dredged sediments are intentionally placed in the downstream thalweg of the river, or on mid-channel islands and shorelines near the river banks. This disposal is economical and maintains a downstream sediment continuum, with the dredged sediments subsequently re-eroded and naturally transported downstream.

4.0 RIVER SEGMENTATION

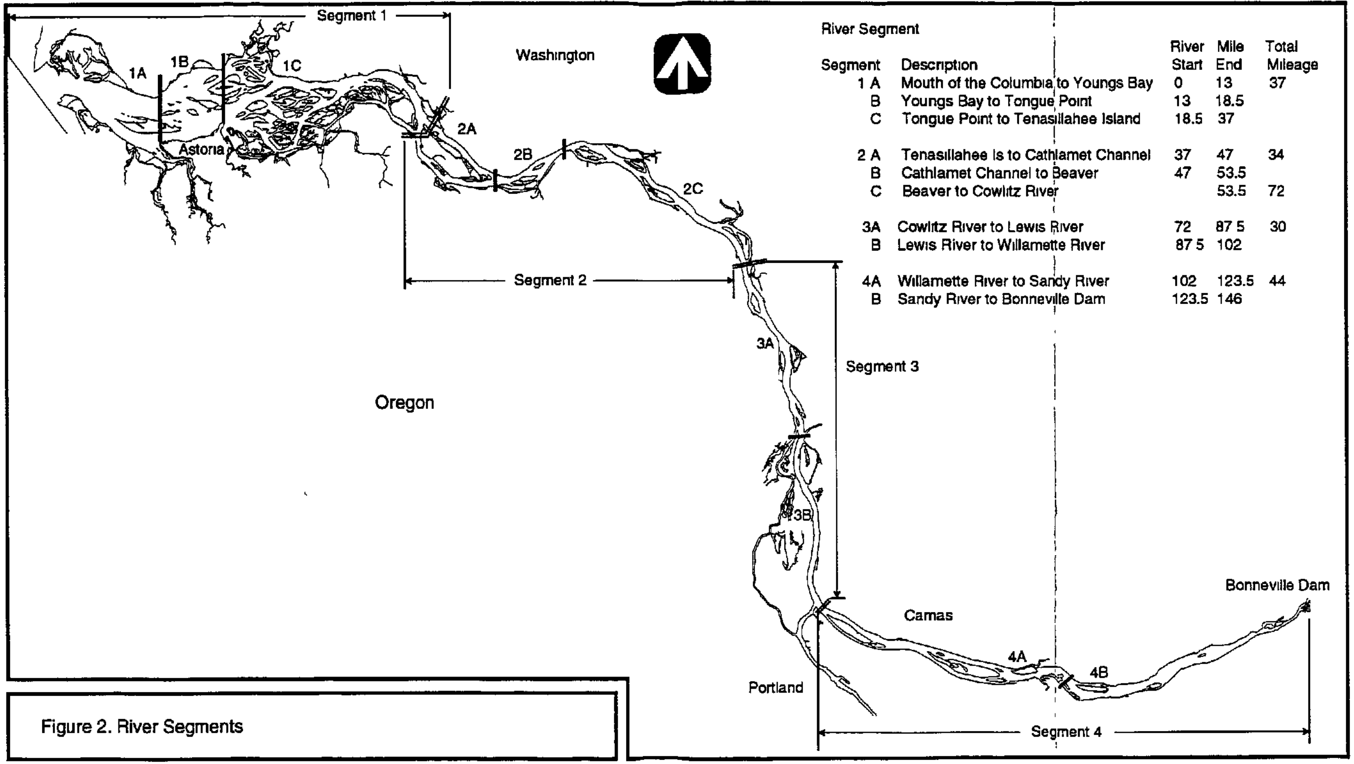
To evaluate the adequacy of existing data it is necessary to separate the lower Columbia River into segments or reaches of similar physical and political characteristics. This segmentation is necessary because of the project or locale-specific nature of existing data. Much study-specific data have been gathered at one location--for example, sediment transport data from the Cowlitz River in the Longview area (COE 1990). In other comparable locations along the river, relatively little data are available. Therefore, it has been necessary to map and prioritize future sampling locations so that data gaps can be filled. The segmentation approach allows the assignment of a higher sampling priority to a river reach of specific physical characteristics where existing information is sparse rather than to a reach where information is abundant

For this study, areas with similar flow and morphologic features are grouped into the same river segment (Figure 2). The three major upriver segment designations are based on confluences with major tributaries, while the downstream boundary of segment 2 is placed between riverine and estuarine portions of the lower Columbia River system. Subsegments within the major four segments are generally based on the major geographic features along the river.

4.1 SEGMENT 1 - MOUTH OF THE COLUMBIA RIVER TO TENASILLAHE ISLAND

River segment 1 encompasses the area of the Columbia River from the mouth (RM 0) to the upstream end of Tenasillahe Island (RM 37). Interest in pollution control, economics of dredging and maintenance, flow regulations from storage projects, shoreline erosion, and the general health of the estuary have all made this segment the most investigated reach of the river.

The upstream boundary of this segment crosses downstream of Cathlamet Channel to Puget Island, then crosses the Columbia River main channel to Bradwood on the Oregon shore. River segment 1 includes



River Segment

Segment	Description	River Start	Mile End	Total Mileage
1 A	Mouth of the Columbia to Youngs Bay	0	13	37
B	Youngs Bay to Tongue Point	13	18.5	
C	Tongue Point to Tenasillahee Island	18.5	37	
2 A	Tenasillahee Is to Cathlamet Channel	37	47	34
B	Cathlamet Channel to Beaver	47	53.5	
C	Beaver to Cowlitz River		53.5	72
3A	Cowlitz River to Lewis River	72	87.5	30
B	Lewis River to Willamette River	87.5	102	
4A	Willamette River to Sandy River	102	123.5	44
B	Sandy River to Bonneville Dam	123.5	146	

Figure 2. River Segments

all of Clifton Channel, and the river's main channel downstream of RM 37. (Cathlamet Channel is included in segment 2.) Segment 1 includes the main body of the Columbia River estuary. An estuary is a semi-enclosed body of water, which is connected to the open sea and is measurably diluted with freshwater from land drainage (Prichard 1955). The region from RM 0 to RM 30 has been described as the estuary, and the reach from RM 30 to RM 37 is described as the transition reach (Ogden Beeman 1984). The Columbia River estuary has been described as an unusual combination of large river discharge and strong tidal currents (Dyer 1973) and classified as a partially mixed estuary (Neal 1972). CREDDP investigation (Jay 1984) has shown that estuary shows fully mixed behavior during high flows and spring tide and stratified behavior during neap tides and low flows.

As discussed, the flow in the Columbia River upstream and within the study reach has been altered by major projects, including multi-purpose dams, flow training devices, and ongoing dredging and disposal (Hines et al. 1978). The estuary is the sink for the sediments washing from a vast river basin of 258,000 mi^2 (Sherwood and Craeger 1990). Sand grain bed sediments are deposited in the estuary as shoals, which move during seasonal river discharge variations. Fine-grained sediments transported as suspended load are deposited in the quiescent areas of the estuary, or transported beyond the mouth into the Pacific Ocean during seasonal flood discharges. Annual dredging is required to maintain the navigational channels, which run from the mouth of the channel through segment 1 and on upstream to about RM 125. Despite the breadth of the estuary, 7.5 miles in some transects, most of the flow is confined to the navigation channels and adjacent deeper waters. The maintained navigation channel has become the thalweg of the estuary, and provides the dominant flow conditions in segment 1. The thalweg channel starts at the center of the river mouth, where it is stabilized by a large rubble mound jetty structure.

The entrance channel at the river mouth is also the widest navigation channel in the estuary, about 2,000 ft at RM 3. The channel narrows and turns south to follow the southern (Oregon) shoreline, passing on the southern side of the Desdemona Sands Shoal at RM 7. It then passes through a sedimentation reach called Flavel Bar at RM 11-12. In the estuary main channel, Flavel Bar is the only sedimentation reach, that receives some fine-grain sediment deposition. This appears to be a result of deepening of the entrance bar and positioning of the salt wedge and fresh water nodal point, which allows fine sediments to settle out of the water column. The presence of fine-grain sediments at the mouth of the estuary can be attributed to the following: 1) the movement of offshore sediments into the estuary, and 2) lack of coarse grain sediments and availability of fine-grain sediments resuspended from Young's

Bay and Young's River due to tidal river conditions (Sherwood et al. 1984). The remainder of the estuary thalweg channel experiences sand size bed load deposition. The channel touches Astoria at RM 13 and heads northwest under the Astoria-Megler bridge, along the Astoria waterfront to Tongue Point, RM 18. The thalweg channel then crosses the estuary towards the northern or Washington bank of the estuary. This crossover channel is positioned between Rice Island (RM 22), and Miller Island (RM 24). Both of these islands are manmade from historical dredged material disposal.

Along the northern side of Miller Sands is a large sandspit originally engineered to enhance flow control and improve natural channel depths for navigation. This spit is now a resource enhancement project and part of the Lewis and Clark National Wildlife Refuge. The thalweg channel passes on the northern side of Miller sands and the refuge, and continues east along the Washington shoreline. The channel follows close to the bank, passing to the north of Pillar Rock Island (RM 27), Woody Island (RM 29), Fitzpatrick Island (RM 31), Welch Island (RM 34), and Tenasillahe Island (RM 37). Here the Cathlamet Channel joins the main navigation channel at RM 37, and Clifton Channel separates from the main channel at RM 37 (COE 1991).

The region between the river entrance (RM 0) and Taylor Sands Shoal (RM 20) has very little bed slope and is reasonably flat and free of obstacles to flow. The region east of Tongue Point and Miller Sands is filled with a number of small islands, vegetated shoals, and secondary channels. The flow pattern in this region is extremely complex. The circulation in the Columbia River estuary (segment 1) is controlled by the tides and the river flow which ranges from a monthly mean low flow of about 65,000 ft^3/sec to a high flow of less than 750,000 ft^3/sec (the 100-year flood limit) (Simenstad et al. 1984), with typical annual discharge at Astoria ranging between 100,000 and 500,000 ft^3/sec. The dominant source of energy throughout the year is the tidal energy, which drives the estuarine circulation. The tide conditions are equalled or replaced only during major flood stage and discharge conditions in the river during the May-June freshet conditions. The complex topography, high tidal energy, and salinity gradients result in a flow condition that varies in three dimensions and over variable time scales—diurnal and semidiurnal tidal variations, and monthly neap to spring tidal variations.

The tidal flow in the Columbia River estuary occurs at diurnal and semi-diurnal frequencies. The neap tidal range is high, about 6 ft at the river mouth, and 6.6 ft at Astoria. The mean diurnal range observed at Astoria is even higher, about 8.5 ft (Neal 1972). Tidal range decreases as a function of river miles beyond Tongue Point (RM 18) (Simenstad et al. 1984). The spring freshet and winter rainfall seasons of high discharge, coupled with tidal flows, induce strong currents and circulation cells within the estuary. The main portion of the flow occurs in the northern channels of the estuary. High tides force the flow into the estuary and up the river portion beyond RM 37. During low river discharges, flood tides meet less opposition and flow reversals have been noted as far upstream as RM 72 (Snyder and McConnell 1973) and RM 95 (Eriksen, K., 21 July 1991, personal communication). During the flood tidal period, the tidal and river flows oppose each other, while during ebb tides the river flow adds to the tidal flow. As a result, there is more energy during the ebb for mixing. Thus, the vertical structure of flow differs for ebb and flood tides. Other vertical variations have been identified as a result of topography and boundary layer effects.

Saltwater intrusion into the estuary is highest during sustained low river discharge periods in summer. Salinity intrusion peaks during the low flow and neap tide conditions. Because there is also greater mixing during spring tide than neap tide, salinity intrusion is greater in neap tide by about 7 to 8 miles than during spring tide (Jay 1984). The salt wedge moves up and down the estuary following the flood and ebb process. Discharge flows out of the river mouth over the salt wedge while salt transfer occurs subsurface above mid-depth. The salt wedge on a seasonal average for the Columbia River reaches up to RM 27 during low discharge conditions. During high flows, the interface between salt and fresh water is found up to RM 14 during flood (Jay 1984). It has also been determined that atmospheric forcing is too weak in comparison to other forces to be of any consequence to the estuarine circulation. The northern channels of the estuary support most of tidal flow, and therefore most of the salt transport upstream into the estuary occurs in the northern channel. The south (navigational) channel supports the river flow out of the estuary.

Sediment transport, which depends on hydrodynamic energy, is tidally dominated at the river mouth and becomes fluvially dominated with distance upriver. The upper Columbia River introduces most of the sediments found on the estuary bed during flood stage discharge. These sediments are redistributed in the estuary during low flow periods. The estuary shows a narrow distribution of sediment, mostly medium sand, from 1.0 to 0.039 mm (0 to 8 phi). The mean grain size in the estuary is 0.176 mm (2.5 phi) (Sherwood et al. 1984).

As discussed, considerable dredging is required to maintain the navigational channels in the estuary. The river mouth (RM 1 to RM 1 6), the outer shoal, and Clatsop Spit (RM 0 to RM 2.6) require annual maintenance dredging. Desdemona Shoal (RM 5.0 to RM 9.4) does not normally extend across the limits of the navigation channel, but instead parallels the channel alignment. Flavel Bar is another shoaling reach along the navigation channel between RM 11 and RM 13. It is positioned at the nodal point for salt and fresh water mixing and experiences some fine-grain as well as sand-size sedimentation. The shoal is also positioned at the outlet area of Youngs Bay and Youngs River in the Columbia estuary, which introduces additional fine-grain sediment in the water column during winter storm conditions in the Youngs River drainage basin. The Tongue Point shoal between RM 18.7 and RM 20.2 requires dredging once every 5 years. The Pillar Rock range of the channel (RM 25 to RM 27.5) requires annual dredging. Similarly, the Brooks Field-Welch reach of the river (RM 28.7 to RM 32.2) has been dredged twice in the past 2 years. Annual dredging previously required along the Miller Sands bar at RM 23 has been alleviated by flow control through island construction.

Sediment from these dredging activities is disposed of predominantly at the Harrington Point Sump or offshore. Harrington Point Sump is located at RM 20, and dredged material is rehandled on a regular cycle from the Sump for final placement on Rice Island.

4.2 SEGMENT 2 - TENASILLAHE ISLAND TO THE COWLITZ RIVER

Moving upstream from segment 1 into segment 2, the Columbia River is transformed from an estuarine to a riverine system. Major tributaries that enter the river in segment 2 include the Cowlitz River in Washington and the Clatskanie River in Oregon. Neither river is generally a factor during spring flooding conditions on the Columbia (COE 1987). In addition, the effects of high ocean tides, particularly in the lower reaches of segment 2, considerably influence flood stages and river velocities.

The upstream limit of segment 2 is positioned at RM 72 immediately upstream of Carrolls Channel. This limit results in the inclusion of the Cowlitz River flow into the Columbia main stem. Dividing the river at this point allows consideration of the effects of Cowlitz River flooding during relatively low Columbia River discharge conditions. Under these conditions, the flow in Carrolls Channel could be significantly reduced or reversed (as occurred during the Mt. St. Helens eruption) and sediment flow would shift into the Columbia River.

In the downstream 9 miles of segment 2, the main channel of the Columbia River divides into two distinct channels passing Puget Island. The primary channel, which is the maintained navigation channel, carries approximately 80 percent of the river's flow. The secondary channel around Puget Island, called Cathlamet Channel, has experienced flow restrictions during the past 30 years by deposition of dredged sediments and construction of pile dike flow control structures. Upstream of Cathlamet Channel (RM 48), the segment 2 channel is predominantly a single flow channel with minor secondary flow in backwater channels such as Wallace, Bradbury, and Fisher Island sloughs. Throughout much of segment 2, the Columbia River and its flood plain are confined by the Coast Range in Oregon and a series of low mountains in southwestern Washington.

Channel hydraulics in this segment are complex, but are relatively well studied. The Portland District COE completed an intensive field and modeling study from Crims Island to Horseshoe Island (also known as Hump Island), RM 53 to RM 60, to determine key erosion areas in the reach. This study demonstrated the magnitude of flow reversals and varying current directions during tidal cycles in the modeled area. A modeling study of a simulated tidal cycle for June 25, 1986 showed that current velocities may vary from 6 ft/sec at low tide to 2 ft/sec upstream on a high tide. Tidal ranges in segment 2 may vary from 12 ft in the lower reach to 4 ft in the upper reach of segment 2 (COE 1991). Studies on the flow conditions and equilibrium cross sections were completed in the upstream reach of this segment following the eruption of Mt. St. Helens (Ogden Beeman 1984). After this study, the equilibrium fill was constructed on the Oregon shore from RM 67 to RM 65. The purpose of the fill was to stabilize natural channel flow velocities and enhance the movement of Mt. St. Helens fine-grain sediments through the shoaling channel reach.

Bed sediments in this segment are primarily composed of fine to medium sand (0.250 to 1 mm) in the navigation channel and secondary channels, with finer grained silts and clays (0.002 to 0.0625 mm) in the backwater channels and overbank (COE 1988). This segment has historically required large amounts of annual maintenance dredging to keep the navigation channel open. The upstream reach of the segment in the Port of Longview area (RM 65 to RM 67) was extensively dredged during 1980 and 1981 in response to the eruption of Mount St. Helens. However, since that time, dredging requirements do not appear to be related to sediment yields from the Cowlitz River. The COE (Eriksen 1991) has explained that the sediments from the Cowlitz River are generally too fine to deposit in the Columbia River navigation channel except during periods of massive sediment discharge associated with winter flooding in the Cowlitz River basin.

Currents are slower in the lower portions of segment 2 than in the upper reaches of the section. This is a result of flow control and channel stabilization structures in the upper reach improving flow velocities coupled with increased channel bifurcation and tidal effects decreasing lower reach currents The reduction in current velocity would suggest that bed deposits would be finer in the lower reach of segment 2 as increasingly finer sands are deposited. COE data generally support the trend towards finer bed sediment in the downstream portions of this segment (COE 1988). Data do not, however, support the existence of massive amounts of Cowlitz River sediments or chemically induced flocculation in this segment of the lower Columbia River.

4.3 SEGMENT 3 - COWLITZ RIVER TO THE WILLAMETTE RIVER

In Segment 3, the Columbia River turns north for nearly 40 miles. The Willamette River enters the Columbia at RM 102 (at the upstream end of Segment 3). Other major tributaries in segment 3 include the Lewis, East Fork Lewis, and Kalama rivers, all in Washington. Flow is regulated on the Willamette and Lewis rivers by upstream dams. Rivers in this reach contribute significantly to winter flooding on the Columbia River, but are generally not a factor during spring freshet discharge from the river's main stem (COE 1987). The upper limit of this segment is immediately upstream of the mouth of the Willamette River, at approximate RM 102.

The main channel of the river in this segment is relatively straight and generally free from mid-channel islands and bifurcations as compared to other segments. The flood plain, which exceeds 5 miles width near Vancouver Lake, contains several large, shallow lakes such as Vancouver Lake in Washington and Sturgeon Lake in Oregon, as well as lengthy secondary channels such as Multnomah Channel, Lake River, and Deer Island Slough.

Channel hydraulics in this segment appear to be the most straightforward in the lower Columbia River. Over 90 percent of the flow in this segment is confined to the main channel (Ogden Beeman 1984). Because the reach does not experience major flow reversals, and is predominantly a single channel with no mid-channel islands, flow direction is dominantly laminar and downstream. Tidal range is generally less than 3 ft upstream and 4 ft downstream of this section during the periods of extremely low discharge.

The lower Willamette River is tidally influenced up to RM 28 and has flow reversals up to Ross Island bridge, about RM 14, during periods of low flow on the Willamette and Columbia rivers. During periods of low flow (generally summer), most of the Willamette River flows down Multnomah Channel to enter the Columbia River at RM 88.

The bed sediments in this reach are primarily composed of fine to medium sand (0.250 to 1 mm) in the navigation channel, silty fine to medium sand (0.0625 mm to 0.25 mm) between the thalweg and the river bank, and silts and clays (0.002 to 0.0625 mm) in the secondary channels, sloughs and overbank. Unlike the upstream and downstream segments, this reach of the river has not required extensive dredging. Maximum dredging activities in this reach occurred immediately following the channel deepening for the authorized deep draft navigation channel. A high quantity of 8 million yd^3 of sediment was dredged per year in the Columbia River upstream of the mouth after the navigation channel deepening began in 1962. Maintenance dredging in this segment of the river has diminished to less than 1 million yd^3 per year in recent years (COE 1986).

4.4 SEGMENT 4 - WILLAMETTE RIVER TO BONNEVILLE DAM

Segment 4 extends from RM 102, immediately upstream of the Willamette River, to Bonneville Dam at RM 146. Major tributaries in segment 4 include the Washougal River in Washington and the Sandy River in Oregon. Flow in this reach is dominantly regulated by upstream storage. As a result, flood peaks are a function of regulation on the upper Columbia River and do not vary like the flood peaks of downstream segments.

Tidal influence at low river stage in this segment varies from 3 ft at the downstream boundary to undetectable at Bonneville Dam. However, river stage may vary as much as 7 ft/day near Bonneville

Dam due to power peaking requirements. Because of the limited drainage area of the tributaries, the tributary inflow in this reach contributes minimally to winter flooding, and is not a factor during spring flooding on the Columbia River (Columbia River Water Management Group 1988).

In this segment, the main channel of the river is slightly meandering and contains several bifurcations caused by mid-channel islands such as Government/Lemon Island (RM 111 to RM 118), Reed Island (RM 126 to 128), and Hamilton Island. The flood plain is generally narrow (less than 1 mile wide) through the Columbia River Gorge, which ends at the Sandy River. The old flood plain is several miles wide near the downstream end of the segment, but flood flow is restricted by maintained flood levees that extend downstream on both sides of the river to Vancouver and Portland.

Channel hydraulics in this segment are somewhat more complex than in segment 3 because of the presence of mid-channel islands and rapidly varying discharges from Bonneville Dam. The reach does not experience flow reversals under any discharge conditions.

Bed sediments in this reach are the most diverse in the study area (COE 1988). Downstream of the Sandy River (RM 121), bed sediments are dominantly composed of fine to medium sand (0.250 mm to 1 mm) in the navigation channel and secondary channels. From the Sandy River upstream to Bonneville Dam, bed sediments range from sand grain to cobble size (0.250 mm to 256 mm). The authorized navigation channel upstream of Vancouver, Washington (RM 105) has lesser dimensions than downstream reaches (300 ft wide and 27 ft deep versus 600 ft wide and 40 ft deep, respectively). As a result, dredging requirements are much less than for segments 1, 2, and 3 (COE 1987). The primary purpose of dredging in this segment is for structural fill or for making cement.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The following eight major conclusions and recommendations can be made as a result of this review:

1. The lower Columbia River System from RM 0 to RM 146 consists of two distinct morphological zones. The system from RM 0 to RM 37 is a type 3 zone, a sediment sink or deposition zone. RM 37 to RM 146 is a type 2 zone. Type 2 is the transfer zone where, for a stable channel, the inflow of sediment can equal the outflow.

2. The morphological zones in the lower Columbia River demonstrate distinctly different physical characteristics of flow and sedimentation. The system from RM 0 to RM 37 incorporates the boundaries of the Columbia River estuary. The system from RM 37 to RM 146 is a lowland river with very small hydraulic slope. Hydraulically, the flow in the estuary is more complex than that in the river. The flow in the river can be described as open channel flow. To determine flows, and predict fate of contaminants and sediment deposition, it is best to analyze and model the estuary and river zones separately and connect the two zones with matching boundary conditions.

3. Since 1939, significant construction projects have altered the hydraulic and hydrologic characteristics of the lower Columbia River. The Bonneville Dam, completed in 1939, significantly modified the flow of Columbia River and its tributaries. While construction of dams for large multi-purpose projects altered the river upstream of Bonneville Dam, dredging and channel stabilization to improve commercial navigation modified the river channel in the lower Columbia River. After completion of these major projects in early 1970s, the hydraulic and hydrologic conditions of the river have changed little. Based on the lack of temporal and physical changes to the river system, the data and studies conducted after 1970 are considered directly relevant to this lower Columbia River study.

4. Fine-grain sediments (silts and clays) and coarse-grain sediments (sand and gravel) remain physically separated during transport and deposition in the river. Fine-grain sediments are transported as suspended sediment and are deposited on the bed only in backwater or flow protected areas upstream of RM 37, and in sheltered or quiescent areas in the estuary. Coarse-grain sediments are transported as bed load and are deposited along the river channel during low flow, then eroded and transported downstream during higher river discharge (over 150,000 to 175,000 ft^3/sec).

5. Given the present flow regulation and continuing channel maintenance, it is estimated that approximately 65-80 percent of the total suspended sediment load input to the study area is carried beyond the river mouth into the ocean. Twenty to thirty-five percent of the suspended load remains in the estuary. Approximately 100 percent of the bed load entering the study area is moved downstream through the riverine system to the estuary, where it remains.

6. Segmentation of the river downstream of Bonneville Dam has been developed based on the hydraulics, hydrology and sedimentation along the river. Four major segments have been defined, but segment lengths may need to be reduced for modeling, and subsegments of each major segment are proposed.

   A. Major Segment 1 - Columbia River from Mouth to Tenasillahe Island.

      Subsegment 1.1. Mouth to Port of Astoria (RM 0 to RM 13). This subsegment includes a part of the estuary that is very wide, but has relatively uniform width. The thalweg in this subsegment is on the Oregon side of the estuary. Bed sediment deposits are sand along the thalweg and secondary channel to the north, and fine-grain sediments in the Baker Bay area and in the Flavel Bar/Youngs Bay area.

      Subsegment 1.2. Port of Astoria to Tongue Point (RM 13 to RM 18). This subsegment includes the channel along the Astoria waterfront to Tongue Point. Providing a deeper navigation channel from the river mouth to Tongue Point has been considered in recent years. The estuary is of uniform width, and the bed sediment in this subsegment is predominantly sand.

Subsegment 1.3. Tongue Point to Grassy Island (RM 18 to RM 30). This subsegment includes the crossover channel from the Oregon side to the Washington side of the estuary. It includes a varying estuary width, with multiple islands. The thalweg is a sand bed, while the adjacent channels in Cathlamet Bay and Grays Bay have fine-grain bed sediments RM 30 marks a conservative limit of salt water intrusion.

Subsegment 1.4. Grassy Island to Tenasillahe Island (RM 30 to RM 37). This subsegment includes the transition reach from estuary to riverine. There is no salt wedge intrusion, but tide conditions create reverse flow. The subsegment is characterized by varying estuary width, multiple islands and back channels, and coarse- and fine-grain sediment deposition.

B. Major Segment 2 - Tenasillahe Island to Cowlitz River.

Subsegment 2.1. Tenasillahe Island to Wallace Island (RM 37 to RM 47). This subsegment includes a bifurcated channel condition around Puget Island. Cathlamet Channel, the secondary channel around Puget Island, is estimated to carry 20 percent of the total channel flow. Both the main channel and Cathlamet Channel exhibit bed load with sand size sediments. The James River outfall at Wauna discharges into the main river channel.

Subsegment 2.2. Wallace Island to Crims Island (RM 47 to RM 54). This subsegment is predominantly a single channel with minor meandering. The subsegment includes a fine-grain secondary channel adjacent to Wallace Island. This reach has been identified as an eroding channel section, losing approximately 2 ft of bed sediment in 10 years.

Subsegment 2.3. Crims Island to Diblee Point (RM 54 to RM 64). This subsegment has extensive flow control structure and channel stabilization. It exhibits a braided, multiple channel planform with several mid-channel islands.

Subsegment 2.4. Diblee Point to Cottonwood Island (RM 64 to RM 72). This subsegment is predominantly a single channel with a complex channel flow at the mouth of the Cowlitz River. Bed sediment is predominantly sand in the main channel with Mt. St. Helens fine-grain bed sediment in the back eddy and quiescent locations along the shore. Longview industry outfalls and the PGE nuclear plant outfall discharges into this reach. The Kalama River mouth is at the upper end of the subsegment.

C. Major Segment 3 - Cowlitz to Wallace River.

Subsegment 3.1 Cottonwood Island to Martin Bluff (RM 72 to RM 79). This subsegment is a two-channel bifurcated reach around Sandy Island, with channel flow control and stabilization. Bed sediment is predominantly sand bed load. The reach includes Port of Kalama shoreline industry and future port development properties.

Subsegment 3.2. Martin Bluff to Lewis River (RM 79 to RM 87). This subsegment is a meandering reach with minor secondary channels. Sediment on the bed in the main channel is sand, while minor secondary channel beds have finer grain sediments. The Port of St. Helens, mouth of Multnomah Channel, and the Lewis River are positioned at the upstream limit of the subsegment.

Subsegment 3.3. Lewis River to Willamette River (RM 87 to RM 102). This subsegment is a single channel with low meandering and relatively uniform width. It is downstream from and includes the mouth of the Willamette River. While the reach has experienced significant historical erosion of its bankline, significant amounts of shoreline have been stabilized. The bed sediment is predominantly sand sediment.

D. Major Segment 4 - Willamette River to Bonneville Dam.

Subsegment 4.1. Willamette River to Lemon Island (RM 102 to RM 111). This subsegment is a bifurcated reach and includes the Oregon Slough channel and the main channel around Hayden Island. The main channel bed is predominantly sand, while Oregon Slough channel is sand and fine-grain sediment. This reach includes the major waterfront development of Portland and Vancouver.

Subsegment 4.2. Lemon Island to Sandy River (RM 111 to RM 121). This subsegment is a bifurcated reach that includes the Government Island Channel and the main channel. The Sandy River and the Washougal River mouth are located at the upstream limit. The James River Camas outfall is also in this reach. The bed in both channels is predominantly sand sediment.

Subsegment 4.3. Sand River to Bonneville Dam (RM 121 to RM 145). This reach is a braided reach with multiple channels and several mid-channel islands. The bed is predominantly sand with gravel at its upper end. This subsegment has no significant inflow other than from Bonneville Dam releases. This reach has been identified as an eroding channel section, losing approximately 2 ft of bed sediment in 10 years and experiencing erosion of the mid-channel island bankline.

7. Since 1970, significant and relevant data have been developed on hydraulic, hydrologic and sediment transport processes in the lower Columbia River. The following data gaps should be supplemented at this time:

A. Bathymetry.

Additional bathymetric data on secondary channels in segments 2, 3 and 4 are required to improve modeling capability. Historical bathymetry of secondary and backwater areas in segment 1 (the estuary) appear acceptable for initial analysis. The final determination of additional bathymetry requirements will depend on model recommendations.

B. Bed Sediments.

Riverine Segments 2, 3, and 4. Bed sediment samples are available for the thalweg and along the main channel bank line. Surface sediment sampling in secondary channels and backwater areas appears very limited or is not available. The reconnaissance survey should focus on secondary channel and backwater locations for sampling in subsegments 2.2, 2.3, 3.2, 4.1 and 4.2. Fine-grain size sediment limits should be identified, and grain size samples should be obtained for characterization.

Estuary Segment 1. Part sediment sampling in Cathlamet and Baker bays provides some information on the quality of fine-grain sediments in the estuary. Additional sampling in Youngs Bay and Grays Bay should be considered to assess sediments and infer water quality history. Additional sediment sampling should be considered in subsegment 1.1 (fine grain in Youngs Bay/Flavel Bar and Baker Bay, coarse sediment near disposal site D), in subsegment 1.3, and subsegment 1.4.

8 One-dimensional numerical models are available and proven for application to the lower Columbia River. There appears to be limited application of the newer generation, two dimensional, finite-element numerical model. However, new technology has been used successfully to determine flow patterns and velocities at varied river discharge conditions in river segment 2 Also, the combination of two-dimensional flow model with transport models has proven successful on other river studies.

The successful application of three-dimensional models for water column and variable density conditions was not identified. Significant variation is observed in the lateral as well as vertical flow structure in the estuary. Simulation of three-dimensional (3-D) flow in the estuary is of utmost importance if one is to be able to identify and predict where the pollutants brought down by the river are likely to be deposited and accumulated. It seems prudent to recommend that the model evaluation report focus on at least a two-dimensional model for quick and relatively inexpensive application but emphasize the 3-D model requirements for the accurate simulation of estuarine dynamics.

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APPENDIX A

GLOSSARY

GLOSSARY

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

HYDRAULIC TERMS

diurnal–having a period of cycle of approximately 1 tidal day.

Flow training devices–Man made structures for maintaining flow along a particular direction for channels and rivers; eg. jetties, dikes.

Hydraulic radius–Equals the cross sectional area of a river cross section divided by the wetted perimeter. For large rivers, such as the Columbia River, the hydraulic radius is nearly the same as the channel width.

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.

Chezy Formula: One of many open channel formulas routinely used in waterway design. The Chezy formula is:

$$V = C(R_h S)^{1/2}$$

Where:
V = Velocity in feet per second
C = Chezy Coefficient
R_h = Hydraulic Radius
S = Energy Slope

Manning's Equation: One of many open channel formulae routinely used in waterway design. The Manning Equation has come into almost universal use in this country for open channel problems. The Manning Equation is:

$$V = (1.49/n)\,(R_h^{2/3} S^{1/2})$$

Where:
V = Velocity
n = Manning's Coefficient
R_h = Hydraulic Radius
S = Energy Slope

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.

Energy gradient--Equals the slope of the river in a particular longitudinal section plus the slope of the velocity gradient in that same section. This term is used to calculate the river level and sediment transport capabilities in a river section at a given discharge.

semidiurnal--having a period of cycle of approximately half a tidal day.

Tidal Forcing-- Periodic ebb and flood tidal motion induced by the gravitational forces causing circulation in the estuary.

Vertically averaged velocity--The velocity of a river varies with depth. The velocity approaches zero at the bed and water interface, generally reaches a maximum near mid-depth and decreases slightly near the surface. The average velocity for a large river, such as the Columbia River is normally calculated by taking the arithmetic average of the measured velocity located at 0.2 and 0.8 times the depth of the river. In the estuary reaches of the Columbia River, the river may be flowing in different directions at different depths and the vertically averaged velocity could be zero.

HYDROLOGIC TERMS

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).

Seasonal flooding--The variability of precipitation in the Columbia Basin means that streamflow (and flooding) is highly seasonal. The Columbia River may have two flood seasons in a year. Flooding may occur during the winter derived from long duration rainstorms west of the Cascade Mountains and during the spring during snow-melt in areas east of the Cascade Mountains.

Freshet--A rapid increase in streamflow caused by relatively intense, short-duration rainfall or snowmelt. A single freshet does not usually result in severe flooding on the lower Columbia River.

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.

GEOMORPHIC TERMS

Bifrications--Separation of river flow to more than one channel.

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.

Reach--A section or segment of a river that has similar hydraulic, hydrologic, and geomorphic characteristics.

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

Thalweg--The deepest portion of the river channel. Sometimes called the "sailing line". A plot of the Thalweg profile by river mile is useful for discussing the slope and hydraulics of a channel.

SEDIMENTATION TERMS

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.

Bed load-- The portion of sediment transported by saltation (skipping) near the bed of the river (less than 3-4 inches form the river bed). Bed load is generally finer that bed sediments.

Bed sediments--The sediments that are found on the river bed. On the Columbia River, the predominate bed sediments are fine- to coarse-sized sand.

Wash load--The fine sized (silts and clays) portion of the sediment transported in a river. Most rivers can transport as much wash load as is yielded to the river.

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.

Planform: View of the geomorphic features as seen from the top. (Equivalent to plan view).

Stokes Drift: Net mass transport induced by the Stokesian wave form of the tidal cycle which has flatter troughs and sharper peaks.