TC-8526-03
FINAL REPORT

# LOWER COLUMBIA RIVER

# BI-STATE PROGRAM

# RECONNAISSANCE SURVEY OF THE LOWER COLUMBIA RIVER

## TASK 3: RECOMMENDATIONS ON CONCEPTUAL MODELING APPROACHES AND NUMERICAL MODELS

MARCH 1992

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

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# 1.0 INTRODUCTION

The Lower Columbia River Bi-State Water Quality Program (Bi-State Program) has been established to assess the ecological health of the lower Columbia River from Bonneville Dam [river mile (RM) 146] to the mouth of the river (RM 0). The primary objective of the program in the first year of the study is to conduct a reconnaissance survey of the river for developing a baseline for future studies.

One of the tasks identified as a part of the study is Task 3, "Review of Physical and Hydrologic Characteristics." The task has been divided into three subtasks to be completed in the form of the following reports.

1. Report on Hydraulic, Hydrologic, Sediment Transport and Geomorphic Characteristics of the lower Columbia River
2. Report on Conceptual Modeling and Recommendations for Numerical Models
3. Final Task Report and Recommendations.

The initial goal of Task 3 was to summarize the physical processes that control river flow, sedimentation, pollutant loading and transport, and subsequently the fate of pollutants. Information required for understanding the hydrodynamic and hydraulic behavior of the river has been presented in the first report. The intent of this second report is two-fold. First, a conceptual model is developed that describes the a system of physical processes such as flow and fate and transport of pollutants. Second, the conceptual model and the characteristics of the lower Columbia will be used to evaluate publicly available numerical models that can be applied for simulations of flow and pollutant transport in the lower Columbia. The report concludes with recommendations for applying the specific models to defined reaches of the river.

# 2.0 CONCEPTUAL MODELING STRATEGY

A suitable conceptual model of the Columbia River must describe and account for the physical processes that drive a dynamic system such as the Columbia. The reach of river under consideration for conceptual modeling runs from the upstream boundary at the Bonneville Dam to the river mouth.

Immense river flow is the dominant physical feature of the Columbia River. The Columbia River is the largest river to empty into the Pacific Ocean and discharges about 260,000 cfs (cubic feet per second) on average (Simenstad et al. 1984). Historically, the maximum discharge record at The Dalles Dam is 1,240,000 cfs on June 6, 1984 (U.S. COE 1986). Flow regulation has limited the 100-year frequency flood in the lower Columbia River to between 700,000 and 750,000 cfs, according to U.S. Army Corps of Engineers (COE) (Simenstad et al. 1984).

Several tributaries contribute to total flow below Bonneville Dam. Nearly 25 percent of the total runoff entering the lower reaches of the river originates west of the Cascade Mountains, and enters the Columbia downstream of Bonneville Dam. The lower Columbia River exhibits a bi-modal river flow. Largest floods occur during the spring between April and June due to snow melt from the higher slopes of the Cascade mountains. Another flood peak occurs in the winter season between November and March and is due to heavy rainfall in the region west of the Cascades. Summer season, July to October, is the low flow period for the lower Columbia River.

Apart from basin drainage and availability of discharge, flow is governed by other factors. Hydraulic features such as bed slope, bed roughness, and channel boundaries play important roles in defining the local nature of the flow. In the river estuary, the river widens and the increased surface area can be affected by atmospheric interactions such as wind velocity and direction, and barometric pressure. While the entire length of the river in the study area is affected by tides, the estuary is most influenced by tides. Flow reversal has been recorded upstream as far as RM 95, but during average flows, reversals of duration greater than 1 hour do not occur beyond RM 75 (Snyder and McConnell 1973).

For the main physical processes of the lower Columbia, a general conceptual-model framework has been developed (Figure 1). The desired product of the conceptual model is constituent transport simulation. All the variables shown in Figure 1 change significantly along the river length because their driving forces vary over the entire study area. To model the river, it is necessary to identify the physically similar reaches, and apply suitable governing equations. A simplified approach to modeling the processes shown in Figure 1 is shown in Figure 2. This simplified model is useful when shorter reaches of the river are considered.

The problem of simulating river health requires simulating river flow, which then has to be related to constituent transport, for determination of the fate of contaminants. The level of modeling sophistication depends on the problem definition. For screening level application, a one-dimensional model might suffice. But for information with greater detail—such as the spatial and temporal concentration distribution of flows, sediments, and pollutants—hydrodynamic simulation of higher sophistication (two- and three-dimensional models) is required

Information on river flow and solutions to contaminant transport may be obtained by four means: field observations, analytical solutions, numerical modeling, and physical modeling.

Field data are important to any hydrodynamic study. By skillful data collection and analysis, it is possible to assess the effects of various physical phenomena such as tides, river discharge, and wind. However, obtaining sufficient temporal and spatial data coverage is often difficult for cost and logistical reasons; this is the case for the Columbia River. For example, there are locations in the river's estuary where data are plentiful, while data are sparse in other regions. Independently, the field data that exist for various reaches of the Columbia River are insufficient and cannot be used directly in developing a predictive tool for flow processes. Nevertheless, the available data on the river are invaluable in defining the boundary condition inputs for the numerical models. These data also help in verification and calibration of the numerical models.

Analytical solutions provide representative solutions and may be used for order-of-magnitude analysis and for studying the trends and behavior of certain quantities. But they often fail to provide the required detail and cannot account for the complex three-dimensional flows that can exist in estuarine circulation. Flows in the Columbia River are complex for several reasons. Discharge shows two peaks, one in spring and the other in winter. Tides are strong relative to low river discharge and their effect is felt as far

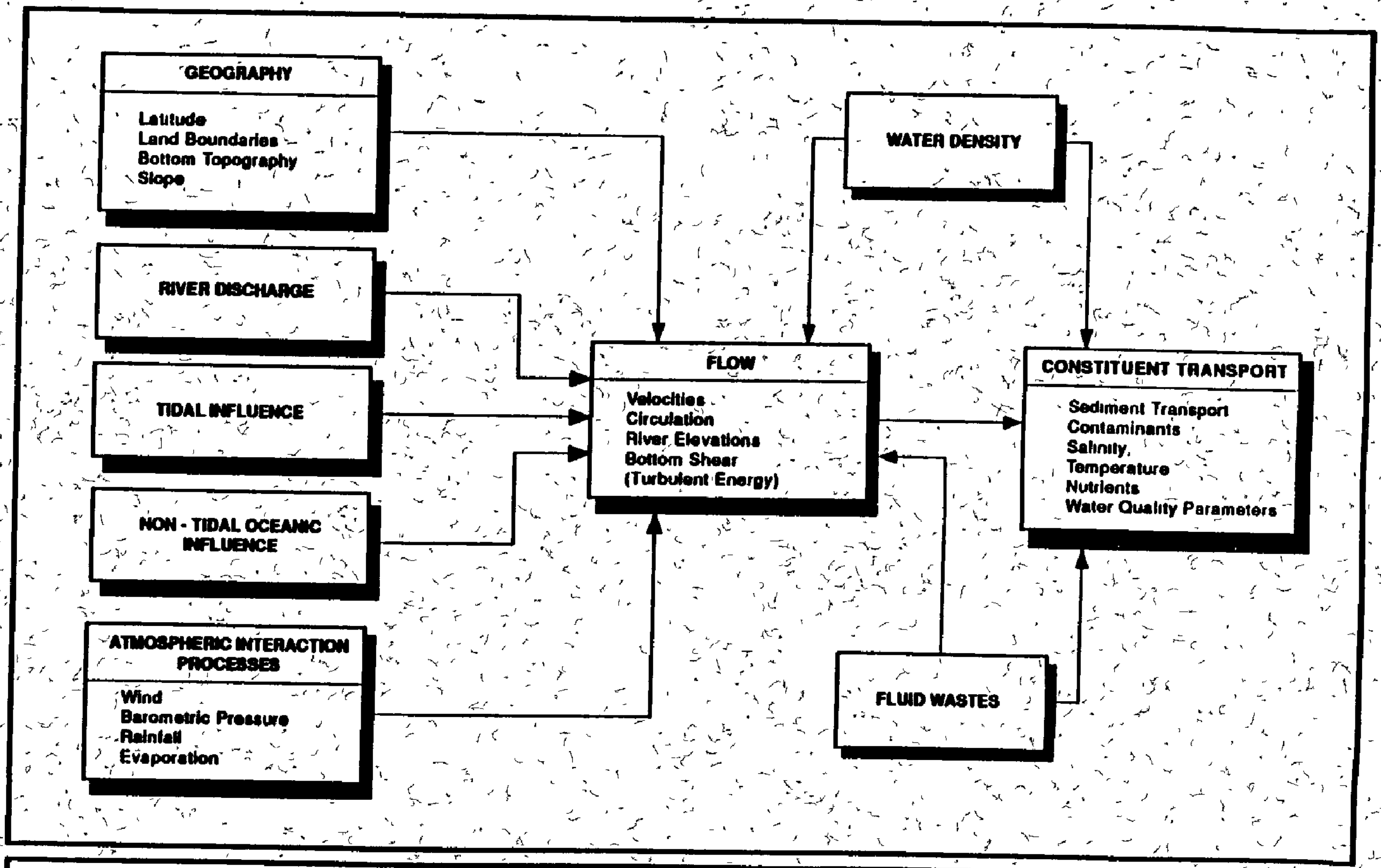

Figure 1. General Conceptual Model Framework for Physical Processes

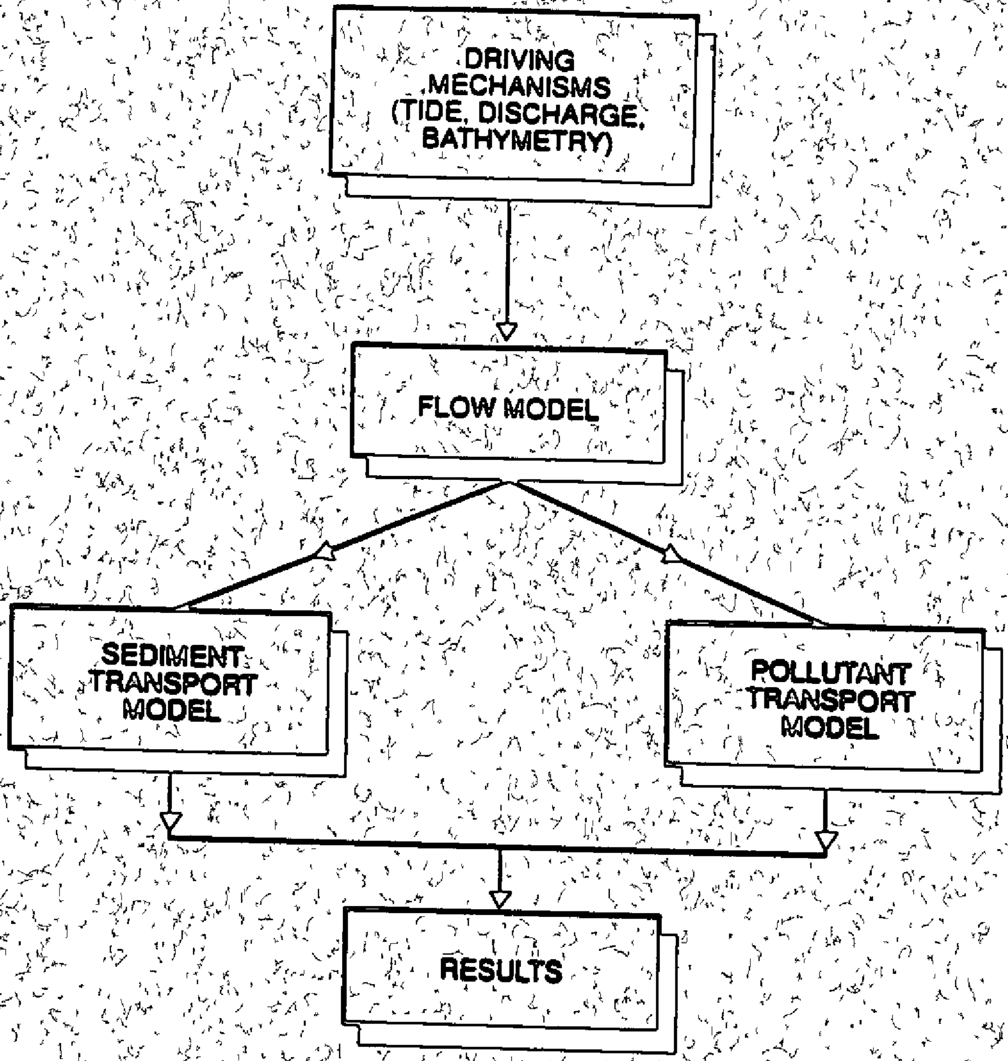

Figure 2. Numerical Modeling Flow Diagram

upstream as Bonneville Dam. In addition, periodic flow reversals, the presence of many mid-channel islands, and the deep navigational channel give the river flow upstream of the estuary a two-dimensional structure. Circulation is further complicated in the estuary by the presence of a salt wedge and many sand-shoals and islands that result in a three-dimensional flow structure. The higher the complexity in geometry and bathymetry, the greater is the error in the analytical solution. Numerical models with a high level of sophistication and accuracy will be required to simulate the complex flows of the Columbia River.

Numerical models vary from simple one-dimensional models to complex three-dimensional models. Models also vary from steady-state solutions to time-dependent models. These numerical models provide more detailed solutions than do analytical solutions. Increased resolution and three-dimensional application require considerable computing resources. Considering recent advances in computer power, two-dimensional models are immediately available, while three-dimensional models are fast becoming a practical tool for hydrodynamic studies.

Physical scale models have provided insight into many processes that would otherwise have been impossible to explain even with the advances in numerical modeling. The main physical processes for the present study—tides, long waves, pollutant discharges, shoaling, and discharge—can be reproduced using a physical model. Clear three-dimensional variations in currents, salinity, density, and pollutant concentrations can be modeled using a physical scale model. Because a scale model of the Columbia River was constructed in 1961 and used for a number of studies as recently as 1983 (McAnally et al. 1983), the existing physical model should be considered for use in studying contaminant and sediment transport in the river. It should be emphasized that the existing model is limited in upstream reach to RM 55. However, the Columbia River exhibits a less complex, uniformly stratified flow upstream of RM 55, making numerical modeling of this section easier. For this reason, as well as cost limitations, constructing a physical model of the remaining 90 miles up to Bonneville Dam is not recommended.

Based on these observations, the following recommendations can be made for predicting the flow, rate, and transport of contaminants in the Columbia River:

- Field data calibrated numerical model for the upper reach of river

- Physical model and or a field calibrated numerical model for the reach downstream of RM 55.

# 3.0 RIVER HYDRODYNAMICS

To select suitable numerical models, it is necessary to identify regions that can be classified into standard categories. For the length of the lower Columbia River under study, three distinct regions may be identified:

1. Estuary Region: RM 0 to RM 37
2. Intermediate Region: RM 37 to RM 54
3. River Region: RM 54 to RM 146.

These regions differ from the four segments presented in the previous report. The segmentation earlier was based on the nature of existing data. That segmentation was done to identify data gaps and assign priorities for future sampling locations. The three regions identified above are based on the hydrodynamic behavior of the river. They represent regions where governing equations for flow and transport are distinctly different and would require separate models for numerical simulation.

## 3.1 ESTUARY REGION: RM 0 to RM 37

A river estuary is a semi-enclosed body of water which is connected to the open sea and is measurably diluted with freshwater from land drainage. In the case of Columbia River, the estuary region is broad compared to the rest of the river. The width increases from a river channel width of about 2,100 ft at RM 53 to a broad estuary of about 47,000 ft in some transects. This change in channel width completely changes the governing processes of the flow. The flow in the estuary region is no longer governed by the hydraulics of open channel river flow. The sudden broadening of width reduces the velocity and momentum flux, at the same time, the mouth of the estuary opens to the ocean. The flows in the estuary are controlled by the tidal influence and surface winds, as well as the downstream river flow.

The Columbia River Estuary has been the subject of a number of investigations Jay (1984) made the following conclusions after analyzing field data and the results of a modeling study by Hamilton (1984):

1. The tidal range in the estuary decreases in the upriver direction due to decreasing momentum.

2. Mixing is greater during ebb tide than flood tide flow due to the dominance of river flow under most conditions.

3. The vertical structure of the flow is different for ebb and flood.

4. Estuary hydraulics are strongly affected by bathymetry

5. Most of the salt enters the estuary near the bed in the northern channel near the Washington shoal and leaves the estuary at mid-depth below the free surface. Salinity intrusions extend up to RM 27 during low flows and neap tides.

These findings indicate a strong three-dimensional flow structure in the estuary. The processes that affect the flow are 1) tidal inflow and tidal elevation, and 2) river flow and free surface slope at the upstream boundary. The fine structure of estuarine flow is controlled by the bathymetry and the boundaries, and is further complicated by a number of shoals and islands.

Although the Columbia River is a complex, three-dimensional, non-steady flow region, general governing equations of continuity and momentum have been developed that may be used to describe the river system. The general equations that govern the estuarine circulation are summarized by Cheng and Smith (1989), and are included in Appendix A.

Solutions to these equations may be obtained by numerical techniques. To reproduce and predict the vertical variations in salinity and currents and the variations in the horizontal plane due to bathymetry and boundary effects, a three-dimensional solution will be required.

## 3.2 INTERMEDIATE REGION: RM 37 to RM 55

The intermediate region (RM 37 to RM 55) is the transition region between the estuary and the river portion of the study area. In this region just beyond the estuary, the flow is still strongly influenced by the tide; however, the vertical stratification no longer exists because salinity is not reported beyond the estuary region. While flow reversals do occur during periods of low flow and high tides, in this region, flow reversal is not as significant as it is in the estuary.

There are a number of islands in the intermediate region such as Tenasillahe Island (RM 37), Puget Island (RM 43), and Wallace Island (RM 49). Most of the flow is in the navigational channel due to its greater depth and hydraulic efficiency. However, there is a significant portion of flow in some of the lesser channels such as the Cathlamet Channel. As a result of the split around the islands, flow takes on a distinct lateral structure. Given the lack of stratification in the vertical direction, the fully three-dimensional governing equations required in the estuary may be simplified to vertically averaged, two-dimensional equations on a horizontal plane.

The governing equations, referred to as Longwave Equations (e.g., Wang and Connor 1975) may be solved on a two-dimensional grid. The computations are considerably simpler than the three-dimensional numerical models ideally required for the estuary. In going from a three-dimensional estuary model to a two-dimensional lateral flow, vertically averaged, model, cost and computational complexity are considerably reduced. However, in doing so, vertical velocity distribution is lost. If resources exist, the three-dimensional model used in the estuary may be extended to cover this intermediate segment of the river. The model based on two-dimensional governing equations may be extended as far as Bonneville Dam, but the flow in the upper river can also be represented by hydraulics of open channel flow.

## 3.3 RIVER REGION: RM 55 to RM 146

In the region between RM 55 and RM 146, the river demonstrates a consistent and dynamic open channel, uni-directional flow. The channel bed slope is consistent and very small. The river planform is either a single channel with slight meander or a multiple, braided channel with islands. The major tributaries that introduce additional river flow from the west side of the Cascades all discharge into the Columbia River along this river region. Upstream boundary conditions are determined by releases from the Bonneville Dam.

The equations that govern the hydrodynamic behavior of the river flow in this region can be based on the more classical concepts of conservation of mass and momentum. In this reach, knowledge of the full three-dimensional flow structure is not required; it is sufficient to use mean-flow quantities in the horizontal direction. The single channel condition lends itself best to the one-dimensional model approach. This is particularly true where no significant backwater sloughs or protected shoreline eddy conditions exist. In reaches of single channels and continuous bank lines, the bed sediment is predominantly a sand or silty-sand sediment. Pollutant material that binds to fine sediments, in suspension, or on the bed, will be transported beyond these reaches. A one-dimensional model is not applicable to the multiple channel conditions because of flow separation and limitations in addressing horizontal flow in more than one direction, unless the model allows a branched network application.

The degree of modeling sophistication appropriate for the river region must be decided. Both one- and two-dimensional models can effectively answer questions of water movement, sediment fate and subsequently, pollutant fate. A general application would favor use of the two-dimensional model that addresses flow quantities laterally, but use of one-dimensional models can provide a less costly method of analysis. In the river region, certain locations of multiple channels or significant tributary inflows require the use of a two-dimensional model approach, and consistently applying the same numerical model methodology along the entire river region is important.

# 4.0 RIVER POLLUTANTS

Various types of pollutants in the form of chemicals, domestic wastes, industrial wastes, and coolants are discharged into the river. These pollutants are transported downstream by several mechanisms. Dissolved chemicals are transported downstream by diffusion and advection, while settleable solids find their way downstream either as suspended load or bed load Some of the chemicals are adsorbed by the bed sediment and are transported through fluvial sediment transport

There are numerical models for all three types of contaminant transport dissolved, suspended load, or bed load. These models vary from the simple one-dimensional type to extremely complicated three-dimensional models The models are often capable of being integrated with their hydrodynamic counterparts. Often the selection of transport models governs the selection of hydrodynamic flow models.

In river pollution analyses, most models follow the concept that river flow drives the transport, dispersion, and dilution of contaminants and contaminant transport. Although independent solutions are not valid in cases where contaminant transport is associated with the transport of large amounts of sediment, satisfactory results can be obtained by selecting suitably short time steps. The questions regarding fate and transport of sediments and contaminants that need to be answered through numerical modeling dictate the complexity of transport models chosen Complexity of transport models decides the level of hydrodynamic flow simulation models to be used

## 4.1 POLLUTANT TYPES

Pollutants discharged to the lower Columbia are characterized in Tetra Tech (1991). Pollutant sources have been classified into three broad categories 1) Point Sources, 2) Non-point Sources, and 3) In-Place Pollutants. Point sources of pollution are defined as discrete sources (such as outfalls) that discharge directly into the waters of the lower Columbia River. Non-point sources refer to pollution that enters the river from dispersed water based or land use activities. In-place pollutants are the land based sources of pollutants (such as hazardous waste sites) which may contribute to non-point pollutant loading to the river.

A total of 54 point sources were identified that discharge wastewater directly into the lower Columbia River via pipes or channels. The types of point source discharges are classified as 1) Domestic Facilities, 2) Industrial Facilities, and 3) Agricultural Facilities. Domestic facilities are municipal wastewater treatment plants that discharge treated wastewater. Industrial facilities are private industrial plants that discharge treated process wastewater, sanitary wastewater, stormwater runoffs, or cooling water. Agricultural facilities are those discharges resulting from plant or animal husbandry.

Non-point sources were identified by summarizing 1) land use in counties bordering the river, 2) available pollutant data from tributaries entering the river, 3) available information on urban stormwater and combined sewer flow, and 4) information on atmospheric deposition to the lower Columbia River.

In-place pollutants include state and federal hazardous waste sites and landfills. These are indirectly connected to non-point sources.

The purpose of modeling pollutant dispersion is to predict water quality under various hypothetical loadings. The physical quantities of interest are known as water quality variables. These include:

- ☐ Primary Variables

    - Quantity of discharge
    - Water depth

- ☐ Associated Quality Variables

    - Temperature
    - pH
    - Turbidity
    - BOD (biochemical oxygen demand)

DO (dissolved oxygen)
Trace metal ions
Conductivity
Radioactivity

Other variables include specific toxic compounds or minerals.

Due to computational constraints, numerical models are capable of handling some of the variables, but not simultaneously. The available data from various pollutant sources will be used for calibration of the models. Once the model is properly calibrated to reproduce data, it may be used as a predictive tool for the selected pollutants being studied.

## 4.2 POLLUTANT TRANSPORT

The dispersion of pollutants from point sources such as outfalls occurs in three steps: 1) Initial Dilution, 2) Deposition of Settleable Solids, and 3) Advection Diffusion Process. Initial Dilution is the rapid turbulent mixing that occurs between the effluent and the surrounding water resulting from the velocity of the jet and the buoyancy in the plume relative to surrounding waters. Following the initial dilution, the plume of diluted pollutant is carried downstream by simple mass transport (advection) and dilutes further by turbulent and fickian diffusion.

The initial dilution and the zone of initial mixing have been studied by the U.S. Environmental Protection Agency for regulatory purposes. Four initial dilution and mixing models UPLUME, UOUTPLM, UMERGE, and UDKHDEN, which are applicable to point sources, are presented in Mullenhoff et al. (1985). More recently CORMIX has been developed, as the result of a search for a more universal model especially suited for applications in bounded channels. CORMIX allows various initial configurations of discharge, density profiles, and uniform currents as the initial conditions for predictions of initial dilutions (U.S. EPA 1990). All these models are applicable only to steady state flow conditions.

After application of one of these initial dilution models, another model must be applied to the diluted plume of effluent in the river The plume contains diluted dissolved contaminants and settleable particles Numerical models have been developed to address dispersion of solids from sewage and other types of discharges, these models solve the dispersion of dissolved contaminants using the advection diffusion equation (Appendix A). SEDOD, a model based on the method in EPA (1982) 301(h) Technical Support Document, and SEDDEP, a model for settleable solids based on Hendricks (1987), may be used in conjunction with flow models to predict the distribution of settleable particles in the bottom sediments.

Thus, after initial mixing, and after having reached steady state, the pollutants may be partitioned into dissolved, suspended, and sediment phases for modeling. The flow transports the contaminants via these phases downstream and each phase needs to be addressed separately in the models that simulate the fate of the contaminants.

For simulations of contaminant transport in a river system, the simplest approach is to assume a one-dimensional steady-state condition This approach would provide adequate results from Bonneville Dam to the estuary. But contaminant transport around the mid-channel islands or sloughs cannot be simulated directly with the one-dimensional approach; a branched one-dimensional model is required. In addition, a one-dimensional approach would be ineffective for simulation of contaminant transport in the estuary Conversely, a model capable of simulating conditions in the estuary would be needlessly complicated and expensive for the rest of the study. It is clear from the extreme changes in the river from the mouth to Bonneville that one numerical model would not be appropriate for the entire study area.

The following are some of the models that could simulate contaminant transport in the Columbia River:

SMPTOX - This is a plug flow one-dimensional model that simulates the fate of the transport of toxics and pollutants from point discharges All three partitioned phases can be simulated simultaneously (LTI 1990).

HEC5Q - This is a COE model capable of simulating multiple reservoirs and river systems. HEC5Q can generate only one-dimensional hydrodynamics and conservative water quality simulations. It can generate long-term simulations, but cannot simulate sediment transport.

HEC6 - This is a COE model capable of simulating sediment transport in river systems and reservoirs. It is a one-dimensional open channel, hydraulics-based model with several sediment transport solver equations It has no water quality simulation capability. HEC6 is a good model for analysis of channel scour.

QUAL2E - This is a U S.EPA stream water quality model It is a one-dimensional model widely used for waste load allocations and discharge permit determinations. It is a quasi-steady model but does not have a component for sediment transport analysis.

WASP4 - This is a U.S EPA model with particularly good capabilities for simulation of conventional and contaminant water quality parameters. It needs to be coupled with DYNHYDE, a flow simulation model

In the intermediate and estuary region, where the flow and bathymetry are more complex, two- or three-dimensional variations must be considered. TABS-2 numerical finite element models consisting of RMA-2V (two-dimensional hydrodynamic simulation) and RMA-4 (two-dimensional simulation of dissolved pollutant transport) may be used (Thomas and McAnally 1985). RMA-4, which solves a weak form of the convective diffusion equation, has general source-sink terms and can accept up to seven pollutant substances, which may be conservative or decay in time. Another model that is two-dimensional but layered in the vertical direction is PACE (CDM 1986). This is a particle tracking model that simulates the fate and transport of dissolved contaminants and effluent solids ELA is a two-dimensional finite element model for mass transport computations, especially suited for point sources because it contains the "puff" algorithm for developing initial spreading of a point source analytically (Baptista 1987) Another code suitable for the estuary and intermediate region is FLESCOT (Onishi and Trent 1982) This is a sediment-contaminant model, which requires a three-dimensional hydrodynamic flow model for coupling.

For cases of non-point sources like the urban and stormwater stream flows, the sources have to be averaged and introduced into standard algorithms as many distributed point sources or a single average point source. Some models are specifically designed to compute the accumulation of wash solids or particulate pollutants in many storm events [e.g., SIMPTM (City of Portland 1989), HSPF (U.S. EPA 1984), SWMM (U.S. EPA 1984)]. Therefore, depending upon the complexity of river reach and the flow, a suitable pollutant transport model may be selected and applied on discrete segments and coupled with the flow models

## 4.3 SEDIMENT TRANSPORT

Sediment transport is an integral part of a dynamic river system such as the lower Columbia River The flow of water over a movable bed causes the motion of bed sediments Lack of sediments induces increased scour and bank erosion. An excess of sediment causes shoaling in a manner such that the turbulent energy available for transport is always balanced by the sediment load Depending on the intensity of flow and sediment grain size, particles may be transported either as suspended or bed sediment load

The study and quantification of sediment transport processes leads to a better understanding of pollutant transport and bed shoaling/scouring processes Contaminants from industrial and municipal discharges affect the water quality and also the sediments The settleable solids portion of the effluent becomes part of the bed sediments. Hubbel and Glen (1973), and Haushild et al. (1973, 1975) have shown that discharges from the Hanford reservation caused formation of radionuclides that concentrated in bed sediments and were distributed downstream by sediment transport.

Many chemicals and trace metals are adsorbed from the dissolved state onto the sediment surface. Studies of Rickert et al. (1977) on trace metal distribution in sediments in Willamette River and Young S.R. (personal communication, 20 October 1989) on pollution in sediments near industrial outfalls indicate clearly that pollutant transport through the sediment phase cannot be neglected in the Columbia River. One reason for studying sediment transport is to assess the bed shoaling behavior of the river. The total suspended load of the river is estimated at 10 million tons/yr (Jay and Good 1978, Haushild et al 1966, Sherwood and Craeger 1990). The total bed load is estimated at 1 to 2 million tons/yr (Ogden Beeman 1984). These estimates do not include the presence of additional sediment brought down by the mud flows caused by the Mt. St Helens eruption.

About 20 to 33 percent of the sand transported as bed load into the estuary is trapped within the estuary (Gross 1972, Hubbel and Glenn 1973, Sherwood et al. 1984). The sand bed load imposes an enormous burden on maintenance of the navigational channels, which tend to shoal with the transported sand An average of more than 7 million m$^3$ of material is dredged every year (Clarain et al. 1979, Eriksen and Fong 1991) from the lower Columbia River Dredging activities are often supported by sediment transport modeling efforts to determine the rates at which the dredged channel will refill with shoaling sediments Activities such as building jetties and breakwaters can cause undesirable effects, as well as the desired stabilizing effects on shoaling Numerical modeling for dredging, jetty, and breakwater construction provides insight into the effects of engineering activities on the flow, and sediment shoaling characteristics. Flow is the primary driving force Depending on bed material, bathymetry, and flow, the concentration of suspended sediment is determined by a three-dimensional mass balance equation for suspended sediments (see Appendix A). Bed load, which has been identified as 10 to 20 percent of the suspended load (Ogden Beeman 1984, Sherwood and Craeger 1990), may be accounted for by calibrating the model with physical data

The state of the art in sediment transport modeling is reviewed by Van Rijn (1989). Several relevant models exist. Depth-averaged one-dimensional models, such as FLOWSED (Johnson 1982), HEC-6 (U S Army COE 1977), and IALLUVIAL (Karim et al 1987) have been used successfully for predicting sediment scour and transport in river channel flow sections Models which are two-dimensional in the horizontal plane, but vertically averaged, include STUDH (Thomas and McAnally 1985), and a formulation by Boer et al. (1989) Three-dimensional approaches are now becoming popular especially in the estuarine regions. Approaches as applied by Sheng (1983), O'Conner and Nicholson (1988), Van Rijn and Meijer (1988) are examples of the successful three-dimensional models. Most sediment transport models are constructed to be compatible with their flow model counterparts . Therefore, selection of a sediment transport model depends somewhat on the selection of the hydrodynamic flow model.

# 5.0 NUMERICAL MODELS OF FLOW AND TRANSPORT

This section examines the most recent developments in numerical models as applied to estuaries and river systems and then reviews models that have been specifically applied to the Columbia River System.

## 5.1 RECENT ADVANCES IN ESTUARY AND RIVER MODELING

The most important recent development affecting hydrodynamic modeling is the availability of relatively inexpensive computing resources, making three-dimensional numerical modeling of estuaries as practical as two-dimensional modeling was a few years ago. For model applications to estuaries, one does not have to resort to approximate two-dimensional models. Cheng and Smith (1989) survey the existing three-dimensional estuarine hydrodynamic and solute transport models. At the same time, it is important to realize that three-dimensional modeling is still in its infancy, and the data requirements for a three-dimensional model are far greater than for two-dimensional models. Three-dimensional modeling is still performed on mainframes and the costs are higher than two-dimensional modeling on microcomputers The choice between three-dimensional and two-dimensional modeling is governed by available resources and the resolution of the solutions desired.

Traditionally, finite difference models have used rectangular grids in horizontal directions for determining the hydrodynamics of estuaries. The CH3D model (Sheng 1989a) attempts to fit the boundaries better using a curvilinear grid. It has been applied to the James River and Hampton Roads estuarine system by Sheng et al. (1989b), and to the study of tidal circulation and salinity transport in Chesapeake Bay by Johnson et al. (1989) A simpler traditional model (CELC3D) using a rectangular grid to predict currents and sediment dispersion was presented earlier by Sheng (1983). A fully three-dimensional hydrodynamic code, TEMPEST (Trent and Eyler 1989), solves equations of mass, momentum, thermal energy, and constituent transport in cartesian coordinates using finite differences. This code was used by Swanson and Mendelsohn (1989) along with the sediment contaminant model FLESCOT (Onishi and Trent 1982) to perform dispersion analysis of the Dartmouth, Massachusetts municipal sewage outfall. The model TEMPEST, coupled with PACE, a particle tracking two-dimensional advective model, was used by Heineman et al. (1989) for simulating ocean outfalls in Massachusetts Harbor.

A new model, ELA, simulates the fate of sediments in estuaries. This model accounts for simultaneous erosion and deposition, and treats flocculation as a second-order process. The governing equations are solved by the Eulerian Lagrangian Finite Element Technique. The compatible flow model is TEA-NL, which works in a frequency domain (Westerink 1985). Blumberg et al. (1989) applied a three-dimensional estuarine and coastal model ECOM 3-D, developed by Blumberg and Mellor (1987), for studying induced circulation of combined sewer overflows in marine tributaries.

Two-dimensional models have existed for almost two decades. While use of three-dimensional models at the entrance of the estuaries is encouraged to account for the salt wedge-induced stratification, beyond the region of salt wedge intrusion, three-dimensional modeling is unnecessary unless bathymetry induces a three-dimensional structure. There have been improvements in the two-dimensional models as well. A highly efficient model that incorporates variable grid size and a fully implicit solution scheme simultaneously was developed by Maa (1990). A finite element model of river and estuarine flows that accounts for moving boundaries was developed by Leclerc et al. (1990).

Similar advances have also been presented in the one-dimensional river modeling schemes. Holly and Rahuel (1990) present a new model SEDICOUP that provides fully coupled solutions of unsteady water and sediment movement, with distinct separations of suspended load and bed load. These features are typically not considered simultaneously by present day techniques.

In spite of the advanced techniques developed, available models or techniques are not applicable to all locations. Multidimensional codes can rarely be used confidently by engineers who have not participated in their development. Data requirements vary from model to model. Keeping these limitations in mind, the three models previously used on the Columbia River before are discussed in the following sections.

## 5.2 ONE-DIMENSIONAL MATHEMATICAL MODEL OF COLUMBIA RIVER TO BONNEVILLE DAM (Callaway 1970)

In this model, the Columbia River from the Pacific Ocean to Bonneville Dam is treated as a series of one-dimensional, vertically and laterally averaged elements. The two-dimensional conditions in the horizontal plane for flows in the estuary and around the island are approached by means of a branched network of connecting channels and junctions.

The Callaway model (1970) was verified using U.S. Coast Guard and U.S. Coast and Geodetic Survey tide table data (U.S. Department of Commerce 1970) for flows. The pollutant dispersion could not be adequately verified due to lack of data. Considering the complexity of the Columbia River system and that computational resources were not as advanced in 1970, this model does a very good job of reproducing the flows and water level at given points in the system. It also simulates space-averaged concentration profiles (see Appendix A for equations).

## 5.3 COLUMBIA RIVER ESTUARY MODEL (Hamilton 1984)

Vertically averaged two-dimensional models are incapable of handling vertical variations of salinity, other processes responsible for tidal mean salt balance, and salinity fields. To investigate the processes dependent on vertical stratification, such as salinity fields, density current circulation or vertical tidal current shears, a model was developed by Hamilton (1984) as a part of the Columbia River Estuary Data Development Program (CREDDP).

This model divides the estuary into a number of interconnected channels, similar to the model of Callaway (see Appendix A for equations). However, the three-dimensional equations of flow and transport are only laterally averaged, and integrated in time, using a formulation similar to an earlier, laterally averaged, depth dependent single channel model developed by Hamilton (1975, 1976).

The depth-dependent single-channel model is advanced to the state where it may be applied to a network of channels. The model provides for variable channel widths and depths, allows for flows across sand banks between channels, and uses depth and time dependent formulas for eddy diffusivities.

Because the model approximates three-dimensional estuary modeling by two-dimensional (vertical) channel flows, computer time is not as intensive as for full three-dimensional models. The model was applied to the Columbia River Estuary, and the hydrodynamics were successfully simulated. Extensive comparisons of the model simulations with CREDDP and National Oceanographic Survey data show good agreement with flow, salinity, and elevation simulation results. The numerical results also confirm many of the data analysis results of Jay (1984)

## 5.4 COLUMBIA RIVER HYBRID MODELING SYSTEM (McAnally et al. 1983)

Simulations or predictions of flows for any complex hydrodynamic system have primarily been done using either a numerical model or a physical model. Both methods have advantages and limitations. The physical models are limited by conflicts of similitude, including the requirement that physical scale modeling laws force some phenomena to be neglected in order to accurately reproduce the dominant processes To simulate inertial forces (dependent upon horizontal length scale) and the drag friction forces (dependent on vertical length scale) simultaneously, as in the case of modeling tides and currents in an estuary, a geometrically distorted model is required. However, a distorted model does not allow the simulation of short period gravity waves. On the other hand, the numerical models may require considerable data for the purpose of verification which may or may not be available. Combining the two methods, using results of a physical model study for input and calibration of a numerical model, is termed a hybrid model.

A physical model of the estuary was constructed at the COE Waterways Experiment Station (WES) in Vicksburg, Mississippi. The model-to-prototype scale is 1:1,500 horizontally and 1:100 vertically, and the salinity ratio for the model is 1:1. The model is equipped with measuring devices for tidal elevations, saltwater intrusion, currents, and freshwater inflow. This model has been used to evaluate alternatives for reduction of navigational channel dredging (McAnally et al. 1983).

The numerical models used for the study of the Columbia River entrance were RMA-2V, RFAC, and STUDH, which are all part of the TABS-2 modeling system at WES (Thomas and McAnally 1985). The generalized program RMA-2V solves the depth-integrated equation of fluid mass and momentum conservation in two horizontal directions using quadratic finite elements. The RFAC model provides estimates of wave conditions over the entrance area, by refracting and diffracting deepwater waves through the entrance to the upper limits of the finite element mesh used by RMA2V and STUDH (McAnally et al. 1983) The model developed by Resio and Vincent (1977) considers waves as a spectrum of energies in direction and frequency It propagates the waves first shoreward and then along shore, over a uniform explicit finite difference grid. The generalized sediment transport program STUDH solves the depth-integrated, advective dispersion equation in horizontal directions for a single sediment constituent

Another model, RMA-4, is a water quality model that solves a form of the convective diffusion equation with general source sink terms. Up to seven conservative substances, with or without decay, can be transported using RMA-4

The hydraulic boundary conditions required by the numerical models are provided by the physical model. The flow model RMA-2V is driven by current and water-surface elevation measurements and computes the flows over the grid using a finite element method of interpolation. The hydrodynamic data are used as inputs to STUDH and RMA4 models for sediment transport and pollutant transport computations, respectively.

The hybrid system for the Columbia River in the river entrance study of McAnally et al. (1983) was verified by comparing the flows and elevation computed by RMA-2V with the model measurements. Verification of sediment transport simulation was done for various grain sizes and dispersion coefficients, to obtain patterns of shoaling similar to the prototype. In spite of limitations of the two-dimensional model used at the estuary entrance, where flow is strongly three-dimensional, the model results were superior to any other two-dimensional model available.

# 6.0 RECOMMENDATIONS OF MODELS FOR COLUMBIA RIVER SYSTEM

The Columbia River Estuary—which features strongly three-dimensional semistratified flow at the mouth, high currents, and many small islands and shoals—is one of the most difficult riverine systems to model The river system itself may be split into three parts 1) the estuary region, 2) the intermediate region, and 3) the river channel flow region Although there are many difficulties associated with modeling this complex system, recently there have been tremendous advances in computing ability What was considered uneconomical a decade ago is now within the scope of many studies. Several numerical models can handle some of the complexities of each of the three regions of the lower Columbia River However, with increasing complexity, there is increasing unreliability associated with these models, unless they have been built specifically for a particular application. Given these limitations, we have taken a two-step approach to recommending numerical models for simulation of the lower Columbia River

## CASE 1. CONSERVATIVE APPROACH

The conservative approach is to use models that have already been used on the Columbia River. These models have already been verified and tested and therefore are quite reliable. The only drawback is that these models may not necessarily be the most numerically and theoretically advanced model available and may yield erroneous solutions if inadvertently used beyond their solution constraints.

Under the conservative approach, the following three models are proposed for application to lower Columbia River:

1 Estuary Region - Hamilton's Model (1984)

2 Intermediate Region - TABS - 2 (Thomas and McAnally 1983)

3. River Channel Flow Region - Callaway's Model (Callaway et al. 1970).

In the original applications, Callaway's model was applied for the entire stretch from the Bonneville Dam to the river mouth. Hamilton's model is superior theoretically because it considers depth dependence and is therefore a better choice for the estuary. However, Hamilton's model is a channel flow model and the vertical detail is not necessary beyond the influence of the tidal prism (RM 37). Therefore, in the intermediate region, the TABS System is recommended. TABS-2, including RMA-2V for the flow simulation, should work well in the intermediate region, which has many small islands and channels. The TABS-2 System would probably be applicable up to Bonneville Dam, but application of a two-dimensional system over a long reach of river may not be economical. Instead, the one-dimensional model of Callaway would be a more cost-effective choice. In situations such as dispersion of effluent from a point source outfall over a large distance, the errors in Callaway's model should diminish relatively quickly. However, Callaway's model would not yield the two-dimensional plume behavior observed a certain distance down the river before the flow is completely mixed laterally. It is recommended that, when detailed distribution of the effluent in the vertical or the horizontal direction is required, higher order models such as Hamilton's model or TABS-2 may be used over short reaches of the river.

## CASE 2. STATE OF THE ART APPROACH

If the purpose of the study is to obtain best possible simulations, and if resources and data exist for verification of an untested model on the lower Columbia River, then a state-of-the-art approach should be pursued.

Regarding the availability of the data, it must be pointed out that the three-dimensional models of the estuary require data that show vertical as well as horizontal distributions. Salinity and current profiles would be required on open boundaries, in place of the point measurements needed for a two-dimensional model. This does not appear to be a problem for the Columbia River Estuary. A physical model of the estuary that can provide the data required from the mouth of the river up to RM 50 exists at the Waterways Experiment Station at Vicksburg, Mississippi. This physical model can be exploited to generate the boundary data that are required by the more sophisticated numerical models.

For the present application to the lower Columbia River, the following three models are recommended

1. Estuary Region - CH3D (Sheng 1986)
2. Intermediate Region - TABS - 2 (Thomas and McAnally 1955)
3. River Channel Flow Region - SEDICOUP (Holly and Rahuel 1991)

CH3D is a recently developed model (Sheng 1986). This fully three-dimensional model has been further developed to quantify long-term calculations and water quality variables in estuaries, lakes, and coastal waters with complex geometries and complex bathymetry. A time-varying three-dimensional model of Chesapeake Bay has been developed by the Waterways Experiment Station, and is considered a state-of-the-art numerical modeling package (Robey and Lower 1991). This model is based on the CH3D code (Johnson et al 1989)

The recommended model for the intermediate region is still the TABS-2 system, a finite element two-dimensional model. The intermediate region does not require the three-dimensional complex simulation, and the availability of the tested TABS-2 hybrid model makes the choice straightforward

Many model options exist in the river region In the river region upstream of River Mile 54, the question is whether to apply a one-dimensional or two-dimensional model approach. The one-dimensional approach is more economical, but limits the near-field and isolated site analysis. Popular river models available include the CARIMA system to simulate unsteady flow in multiple-connected networks of rivers, canals and inundated areas (SOGREA, Grenoble, France), and the Danish Hydraulic Institute's SIVA system 21, for multiple-connected rivers and canals. IALLUVIAL, a quasi-steady water and sediment routing model for long-term prediction of water surface and bed evaluation, is also available. These three models are all one-dimensional models. The latest in river flow models is SEDICOUP, which is reported to overcome the weaknesses of existing models and adhere to existing conservation laws (Holly and Rahuel 1991). Therefore, SEDICOUP is recommended as the one-dimensional model for the river length from RM 55 upstream to Bonneville Dam

A two-dimensional model provides greater detail for near-field analysis of pollutant fate, and a greater numerical detail of the waterway flow, but at greater cost for field data and model development than a one-dimensional model. It is considered likely, however, that the technical superiority of a two-dimensional model will eventually make this the standard for modeling river systems such as the river channel flow region of the lower Columbia. Development of a two-dimensional model such as the TABS-2 system for the river region is preferred, provided the budget is available and long-term application of a numerical model to river management is the objective.

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# APPENDIX A

# RELATED EQUATIONS

## APPENDIX A

### GENERAL EQUATIONS GOVERNING ESTUARINE CIRCULATION (Cheng and Smith 1989):

Continuity Equation

$$\nabla \cdot \vec{U} = 0$$

Equa 1

x-Momentum Equation

$$\left(\frac{\partial u}{\partial t} + \vec{U}\cdot\nabla u - fv\right) = -g\frac{\partial \zeta}{\partial x} + \nabla_{xy}(A_h\nabla_{xy}u) + \frac{\partial}{\partial z}(Av\frac{\partial u}{\partial z}) - \frac{g}{\rho o}\int_z^{\zeta}\frac{\partial \rho}{\partial x}dz'$$

Equa. 2

y-Momentum Equation

$$\left(\frac{\partial v}{\partial t} + \vec{U}\cdot\nabla v + fu\right) = -g\frac{\partial \zeta}{\partial y} + \nabla_{xy}(A_h\nabla_{xy}v) + \frac{\partial}{\partial z}(Av\frac{\partial v}{\partial z}) - \frac{g}{\rho o}\int_z^{\zeta}\frac{\partial \rho}{\partial y}dz'$$

Equa. 3

Pressure is assumed hydrostatic

$$\frac{\partial P}{\partial z} = -\rho g$$

Equa. 4

Conservation Equation for a contaminant $^{C_j}$, or a conservative scaler like T or S (temperature or salinity)

$$\frac{\partial C_j}{\partial t} + \vec{U}\cdot\nabla C_j = \nabla_{xy}(k_h\nabla_{xy}C_j) + \frac{\partial}{\partial z}(k_v\frac{\partial}{\partial z}C_j)$$

Equa. 5

where:

$j$ = 1,2...

**Equation of State**

$$\rho = \rho(S,T)$$

Equa 6

where.

$t$ = Time

$(x,y,z)$ = Cartesian coordinates

$U$ = $iu + jv + kw$, is the velocity vector

$i, j, k$ = Unit vectors

$(u,v,w)$ = Components of $U$ in $(x,y,z)$ directions

$T$ = Temperature

$S$ = Salinity

$P$ = Pressure

$f$ = Coreolis parameter

$g$ = Gravitational acceleration in -K direction

$$\nabla = i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial z}$$

$$\nabla_{xy} = i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y}$$

$\rho$ = Density of water

$\rho_o$ = Constant reference density

$A_h$ and $K_h$ = Horizontal eddy viscosity and diffusivity coefficients

$A_v$ and $K_v$ = Vertical eddy viscosity and diffusivity coefficients

## THREE-DIMENSIONAL MASS BALANCE EQUATION FOR SUSPENDED SEDIMENTS (Van Rijn 1989)

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial x}(uC)+\frac{\partial}{\partial y}(vC)+\frac{\partial}{\partial z}((w-w_s)C)-\frac{\partial}{\partial x}(e_{s,x}\frac{\partial C}{\partial x})-\frac{\partial}{\partial y}(e_{s,y}\frac{\partial C}{\partial y})-\frac{\partial}{\partial z}(e_{s,z}\frac{\partial C}{\partial z})=0$$

Equa 9

where

$C$ = Sediment concentration
$u,v,w$ = Fluid velocity components in $x,y,z$ directions
$\epsilon_s$ = Sediment mixing coefficient
$w_s$ = Particle fall velocity
$t$ = Time
$x,y,z$ = Cartesian coordinates

The flows $u,v,w$ are obtained from the results of the flow model.

## ONE-DIMENSIONAL MATHEMATICAL MODEL - CALLAWAY 1970

**The flows in the channels are obtained by the finite difference solution of equations of continuity and momentum**

$$\frac{\partial h}{\partial t} + \frac{1}{b}\frac{\partial q}{\partial x} = 0 \ , \ q = Au$$

**Equa 10**

$$\frac{\partial u}{\partial t} + u\,\frac{\partial u}{\partial x} + g\,\frac{\partial h}{\partial x} + k|u|u = 0$$

**Equa. 11**

**where:**

**u = Flow velocity in x direction**
**h = Water depth**
**q = Volume flow rate**
**b = Width of the channel**
**k = Roughness coefficient**
**A = Cross-sectional area.**

**The computed flow velocities are used as input to the advection diffusion equation, and solutions obtained for the transport of any conservative substance, and any coupled BOD, or DO calculations. Operational form of the advection diffusion equation used in one-dimensional model is:**

$$\left[\frac{\partial}{\partial t} - \frac{\partial}{\partial x}\left(D_L\frac{\partial}{\partial x}\right) + u\,\frac{\partial}{\partial x}\right](L,C,T..) = \sum S$$

**Equa. 12**

**where:**

**$D_L$ = Coefficient of longitudinal dispersion**
**L = BOD concentration**
**C = DO concentration**
**T = Temperature**
**S = Source and sinks**
**u = Vertically averaged velocity.**

**Temperature, a variable not commonly treated in most models, is solved as a dependent variable. Meteorological variables are used as input for heat budget computations for prediction of temperature.**

## COLUMBIA RIVER ESTUARY MODEL (HAMILTON 1984)

The equations of the model using the Bousnesq approximation for a narrow channel of variable width and depth are:

Continuity

$$b_\zeta \frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} = 0$$

Equa. 13

$$bw = -\frac{\partial}{\partial x} \int_{-h}^{z} bu \; dz$$

Equa 14

Momentum Conservation

$$\frac{\partial u}{\partial t} + \frac{1}{b} \frac{\partial}{\partial x} (buu) + \frac{1}{b} \frac{\partial}{\partial z} (buw) = -g \frac{\partial \zeta}{\partial x} - \frac{g}{\rho} \int_{z}^{\zeta} \frac{\partial \rho}{\partial x} dz + \frac{1}{b} \frac{\partial}{\partial z} \left(bNv \frac{\partial u}{\partial z}\right) - \frac{k_s |u| u}{b} [1 + ($$

Equa. 15

Salt Conservation:

$$\frac{\partial}{\partial t} (bs) + \frac{\partial}{\partial x} (bus) + \frac{\partial}{\partial z} (bws) = -\frac{\partial}{\partial x} \left(bk_h \frac{\partial s}{\partial x}\right) - \frac{\partial}{\partial z} \left(bk_v \frac{\partial s}{\partial x}\right) = 0$$

Equa. 16

where:

x and z are coordinates in the plane of undisturbed water surface.
x is along the channel and z is vertically upwards
$t$ = Time
$\zeta$ = Elevation of the water surface above the undisturbed plane.
$u, w$ = Velocity components in x and z directions.
$\rho$ = Density of water
$s$ = Salinity
$h$ = Depth, a function of x only
$b$ = Width, a function of x and z
$b_\zeta$ = Channel width at $z = \zeta$
$k_h$, $k_v$ = Vertical and horizontal eddy diffusivities
$Nv$ = Vertical eddy viscosity coefficient
$k_s$ = Side wall friction coefficient
$g$ = Acceleration due to gravity.

These equations are solved using the finite different method.

## COLUMBIA RIVER HYBRID MODELING SYSTEM (McAnally et al. 1983)

The form of the solved equations in RMA-2V model is:

$$h\frac{\partial u}{\partial t} + hu\frac{\partial u}{\partial x} + hw\frac{\partial u}{\partial z} + gh\left(\frac{\partial h}{\partial x} + \frac{\partial a_o}{\partial x}\right) - \left(\frac{\epsilon_{xx}}{\rho}\frac{\partial^2 u}{\partial x^2} - \frac{\epsilon_{xy}}{\rho}\frac{\partial^2 u}{\partial y^2}\right)h$$

$$-2\omega vh\sin\phi + \frac{gun^2}{C^2}(u^2+v^2)^{1/2} - \zeta V_a^2\cos\psi = 0$$

Equa 17

$$h\frac{\partial v}{\partial t} + hu\frac{\partial v}{\partial x} + hv\frac{\partial v}{\partial y} + gh\left(\frac{\partial h}{\partial y} + \frac{\partial a_o}{\partial y}\right) - \left(\frac{\epsilon_{yx}}{\rho}\frac{\partial^2 w}{\partial x^2} - \frac{\epsilon_{yy}}{\rho}\frac{\partial^2 v}{\partial y^2}\right)h$$

$$+2\omega uh\sin\phi + \frac{gvn^2}{C^2}(u^2+v^2)^{1/2} - \frac{\zeta}{h}V_a^2\sin\psi = 0$$

Equa. 18

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(uh) + \frac{\partial}{\partial z}(wh) = 0$$

Equa. 19

where,

u = Horizontal flow velocity in the x direction
t = Time
x = Distance in the x direction (longitudinal)
v = Horizontal flow velocity in the z direction
y = Distance in the y direction (lateral)
g = Acceleration due to gravity
h = Water depth
$a_o$ = Elevation of the bottom
$\epsilon_{xx}$ = Normal turbulent exchange coefficient in the x direction
$\rho$ = Fluid density
$\epsilon_{xy}$ = Tangential turbulent exchange coefficient in the x direction
$\omega$ = Angular rate of earth's rotation
$\phi$ = Latitude
C = Chezy roughness coefficient
$\xi$ = Coefficient relating wind speed to stress exerted on the fluid
$V_a$ = Wind velocity
$\psi$ = Angle between wind direction and x axis

$\epsilon_{yx}$ = Tangential turbulent exchange coefficient in the y direction
$\epsilon_{yy}$ = Normal turbulent exchange coefficient in the y direction

The equation of sediment advection and dispersion solved in STUDH model

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} = \frac{\partial}{\partial x}\left(D_x\frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y\frac{\partial c}{\partial y}\right) + \alpha_1 c + \alpha_2$$

Equa 20

where:

(x,z) = Horizontal plane
c = Concentration of sediment
u = Velocity in x direction
W = Velocity in z direction
$D_x$ = Dispersion coefficient in x direction
$D_y$ = Dispersion coefficient in y direction
$\alpha_1$ = Coefficient of concentration dependent source/sink
$\alpha_2$ = Coefficient of source/sink.