WILLAMETTE RIVER AND COLUMBIA RIVER WASTE LOAD ALLOCATION MODEL

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Abstract: A hydrodynamic and water quality model of the Lower Willamette River was developed to evaluate management alternatives designed to improve water quality. The Lower Willamette River is located in Oregon and drains a watershed covering 11500 square miles consisting of forested, agricultural, and urban lands. Inflows include treated municipal wastes and industrial effluents along with non-point sources from agricultural, silvicultural and urbanized land. The model was designed to address temperature, dissolved oxygen, algae, pH and bacteria concerns. The Corps of Engineers two-dimensional, laterally averaged, hydrodynamic and water quality model CE-QUAL-W2, Version 3 was applied. CE-QUAL-W2 consists of directly coupled hydrodynamic and water quality transport models and simulates parameters such as temperature, algae concentration, dissolved oxygen concentration, pH, nutrient concentrations and residence time. The model domain covers a total of about 126 river miles, including the Lower Willamette River from its intersection with the Columbia River upstream to Canby Ferry (RM 35.0) and the Columbia River from Bonneville Dam (RM 144.5) to Beaver Army Terminal (River Mile 53.8). Modeling of the Columbia River was necessary to simulate tidal fluctuations and influxes of Columbia River water into the Lower Willamette. Major tributaries and major NPDES point sources were point inflows to the system model. The ability to model multiple water bodies was a feature of CE-QUAL-W2 Version 3 and allows the simulation of river, reservoir or estuary sections with varying bottom slopes separated by dams and other hydraulic structures. The model was calibrated for the summers of 1993, 1994, 1997, 1998, and 1999. Hydrodynamics were calibrated first followed by temperature and water quality. Root mean square error of model water level predictions was generally less than 0.05 m. Because of the short residence time within the model domain, the development of accurate boundary conditions was essential for good model calibration.

INTRODUCTION

The Willamette River system is a 11,500 mi^2 watershed and drains through the Lower Willamette River from river mile (RM) 0 to RM 35 (Canby Ferry), Figure 1. The river passes through the Portland, Oregon metropolitan area before its confluence with the Columbia River at Columbia RM 106. The Columbia River is tidally influenced from the Pacific Ocean to the tailrace of the Bonneville Dam at RM 145. The Lower Willamette River is also tidally influenced from RM 0 (confluence with the Columbia) to the Oregon City Falls at RM 26.8.

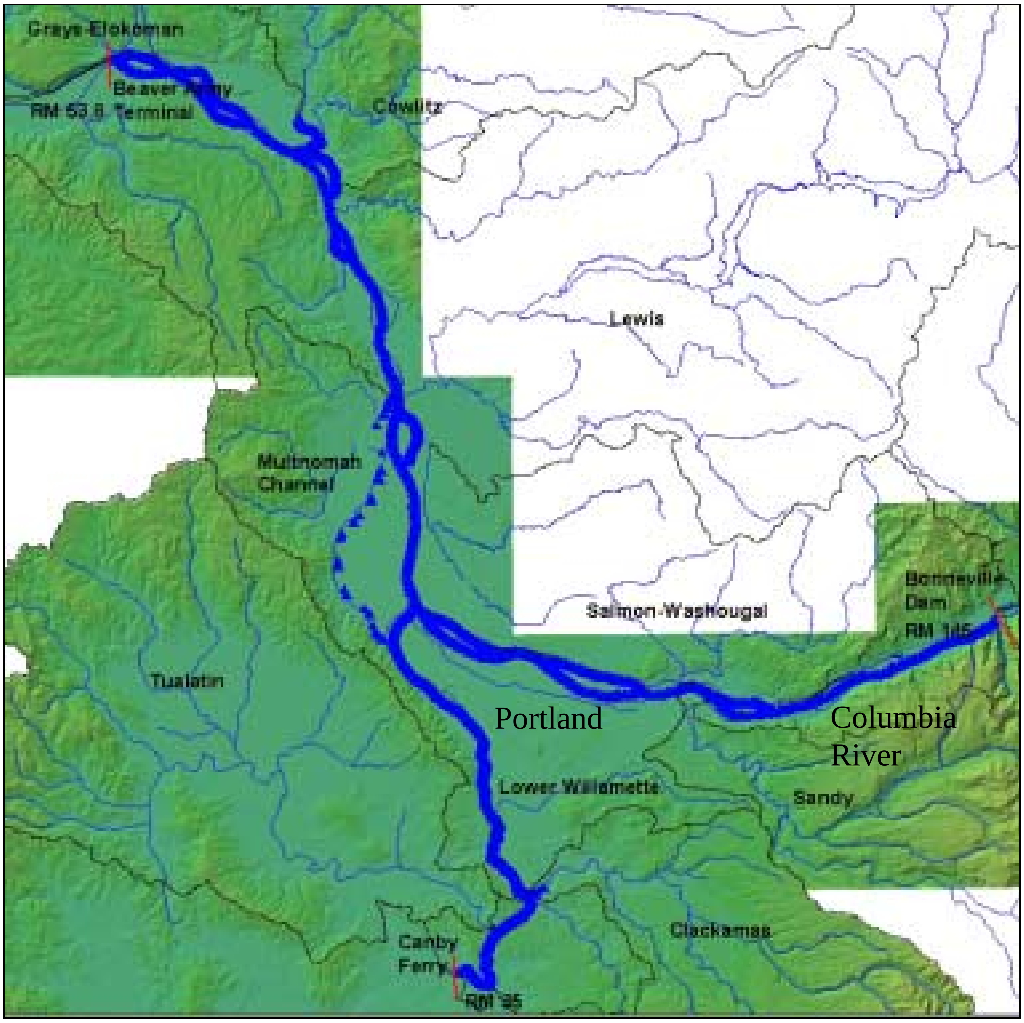

Figure 1. Lower Willamette and Columbia River model region

Water Environment Services of Clackamas County was in the process of planning upgrades on several of its sewage treatment plants which discharge into the Lower Willamette River and required modeling information to assess the impact of their future discharges to the Willamette River. The goals of the modeling effort were to:

- Construct a computer simulation model of the Lower Willamette River system including part of the Lower Columbia River and the Willamette River above the Falls at Oregon City;
- Calibrate the model to field data ensuring that the model accurately represents the system physics and chemistry (flow, temperature, dissolved oxygen and nutrient dynamics);
- Use the model to evaluate management scenarios for the sewage district.

MODEL DEVELOPMENT

<u>Model Selection:</u> A hydrodynamic and water quality model, CE-QUAL-W2 Version 3 (Cole and Wells, 2000), was applied to the Willamette-Columbia system. CE-QUAL-W2 is a two dimensional (longitudinal-vertical), laterally averaged, hydrodynamic and water quality model that has been under development by the Corps of Engineers Waterways Experiments Station. CE-QUAL-W2 Version 3 was proposed as the most appropriate model for the Lower Willamette system primarily because it contained the following elements:

- Two-dimensional, dynamic hydrodynamics and water quality model capable of replicating the density stratified environment of the tidally influenced river sections as well as the sloping river channel sections. This is especially important when there are deep "holes" where a 1-D model would predict erroneously flow through the entire cross-section of the "hole".
- River-estuary and hydrodynamic-water quality linkage is transparent for the Model User.
- The model can handle two-dimensional branches added on to the main stem of the Willamette River such as the lower reach of the Clackamas River as well as flow around islands.
- The CE-QUAL-W2 Version 3 code has many state-of-the-art model refinements that reduce numerical errors and improve the accuracy of model simulations.

<u>Modeling Periods:</u> Based on the availability of field data, the model simulation time periods were the summers, May 1st to October 1st, for the years, 1993, 1994, 1997, 1998 and 1999. In addition to modeling the hydrodynamics and temperature, the Willamette River model also simulated: dissolved and particulate non-living organic matter (both refractory and labile components), ammonia, nitrate, dissolved PO_4, algae, TDS, pH, dissolved oxygen, and bacteria.

Conceptually the model elements, shown in Figure 2, are:

- Willamette River above the Oregon City Falls
- Willamette River below the Oregon City Falls
- Columbia River with side channels
- Multnomah Channel
- Lower Clackamas River and adjacent gravel pit.

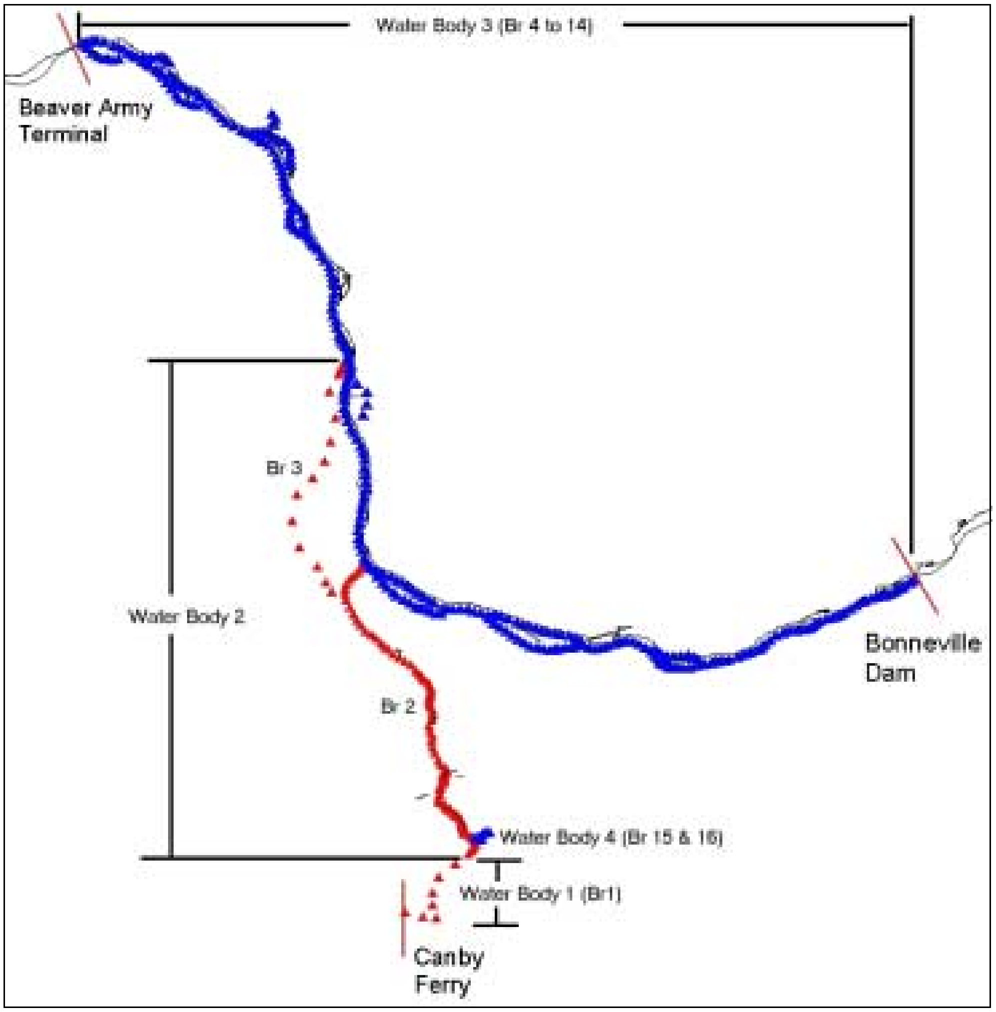

Figure 2. Conceptual Layout of the Lower Willamette River System Model (Points Represent Model Segments).

Model Boundaries: The model boundary conditions include inflows and water quality, meteorological conditions, and point source inflows and water quality characteristics. Many local, state and federal agencies have been collecting data in the Lower Willamette and Columbia Rivers. Meteorological data were collected at Portland International Airport and include air temperature, wind speed, wind direction, dew point, and cloud cover. The Portland International Airport was selected because it contained the longest historical record of data and represents meteorological conditions in the model domain.

The majority of the tributary inflows to the Columbia and Willamette River were considered in the model. Nevertheless, a small number of these tributaries were not characterized because flow information was not available. A GIS analysis determined the drainage area not considered in the model was only about 0.34% of the total drainage area.

Point source data for the Columbia and Willamette Rivers were collected from the Discharge Monitoring Reports (DMR) provided by Oregon Department of Environmental Quality (DEQ) and Washington Department of Ecology (WADOE). The Clean Water Act requires that any discharger of "pollutants" from a point source into a water body have a National Pollution Discharge Elimination System (NPDES) permit. The NPDES permit may define minimum or maximum limits of discharge constituents and may require periodic monitoring and reporting of the discharge. This reporting is submitted to the local branches of the EPA (Permit Compliance System) and DEQ/WADOE in the form of a Discharge Monitoring Report (DMR).

Model Grid: The model grid was developed based on detailed cross sections for the Columbia River and the Willamette River provided by the U. S. Army Corps of Engnieers (Knutson, 2000). The model grid included cross sections from RM 145 (Bonneville Dam) to RM 53.8 (Beaver Army Terminal) on the Columbia River and from RM 0 to RM 24 (Oregon City Falls) on the Willamette River. Cross-sections of the Willamette River between the Oregon City Falls (RM 26.8) and Canby Ferry (RM 35) were provided by Portland General Electric (PGE, 1998). These cross-sections were based on a survey done by the National Oceanic and Atmospheric Administration (NOAA) in October 25, 1997. The model grid was developed for 4 water bodies. Figure 2 shows a layout of the model grid. A total of 16 branches make up the 4 water bodies in the model. The Willamette River above the Oregon City Falls was modeled as one branch within a waterbody. The second waterbody consisted of two branches, the first was the mainstem of the Willamette River and the second was Multnomah Channel. The Columbia River represented a third waterbody with 11 branches. The first branch was the main channel of the Columbia River and the remaining 10 branches were at tributary inflows or side channels around islands in the river. The fourth waterbody represented the lowest reach of the Clackamas River and a gravel pit cove on the side. Segment size was based on the spacing of the cross-sections in the bathymetry data. Layer thickness in the model was 2 meters throughout, and the model consists of a total of 484 segments. Table 1 summarizes the specifics of the model grid. Vertical grid resolution for the Willamette River and Columbia River reaches were shown in Figure 3 and Figure 4, respectively.

Table 1. Model Grid Layout Specifications

Water bodies	Branches	# of segments	Segment length	Layer Thickness
4	16	483	80 m – 4361 m	2 m

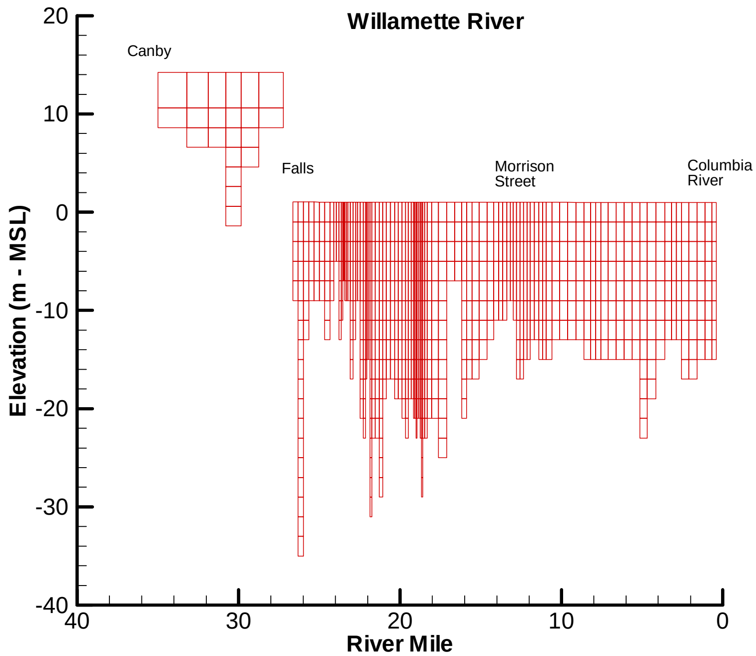

Figure 3. Lower Willamette River vertical grid resolution (note variable longitudinal segment spacing and vertical grid resolution).

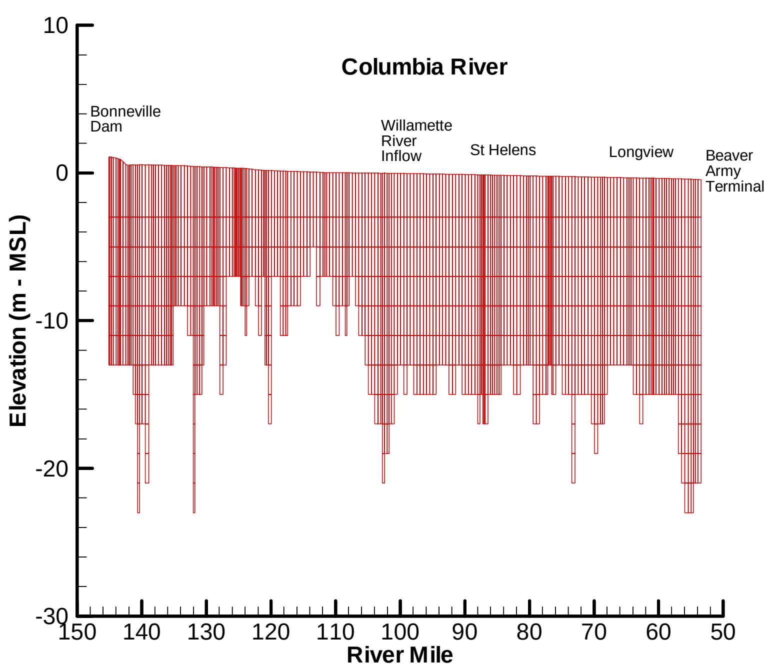

Figure 4. Columbia River vertical grid resolution.

MODEL CALIBRATION

Hydrodynamic Calibration: The first step in the calibration process was to ensure the model correctly predicted water levels and flow rates at measuring stations in the Willamette and Columbia River. Water level data used for calibration originated from 2 Willamette River gauging stations and 5 Columbia River stations. Flow data used in calibration existed for 1 Columbia River station and 1 Willamette River station. Manning's *n*, or friction coefficient, was the only model coefficient used for calibrating water level and flow rate predictions with data. Model friction factors were adjusted until there was reasonable model-data agreement in water level and flow rate. For all simulation years Mannings *n* was calibrated to a value of 0.025 for the whole model domain. Root mean square error of model water level predictions was generally less than 0.05 m for the summer months. Figure 5 shows water level predictions compared with data in the Lower Willamette where the tidal range was approximately 1 meter. Figure 6 shows a comparison between and flow predictions and data and illustrating reversing flow that may occur during dry periods.

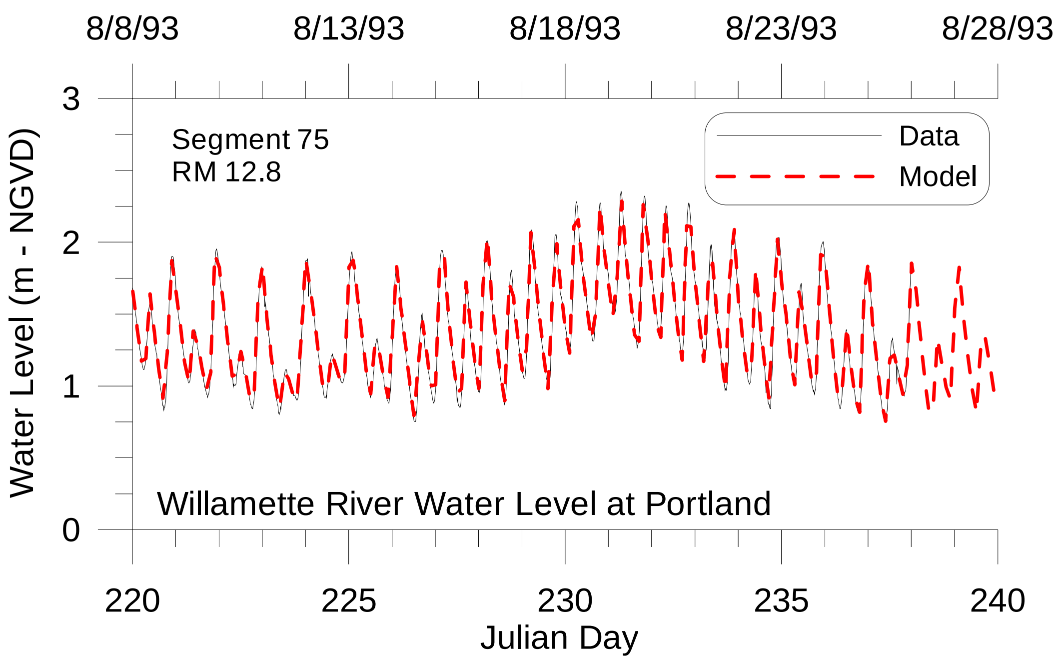

Figure 5. Comparison between model water level predictions and data in the Willamette River. The fluctuations in water level are due to tides.

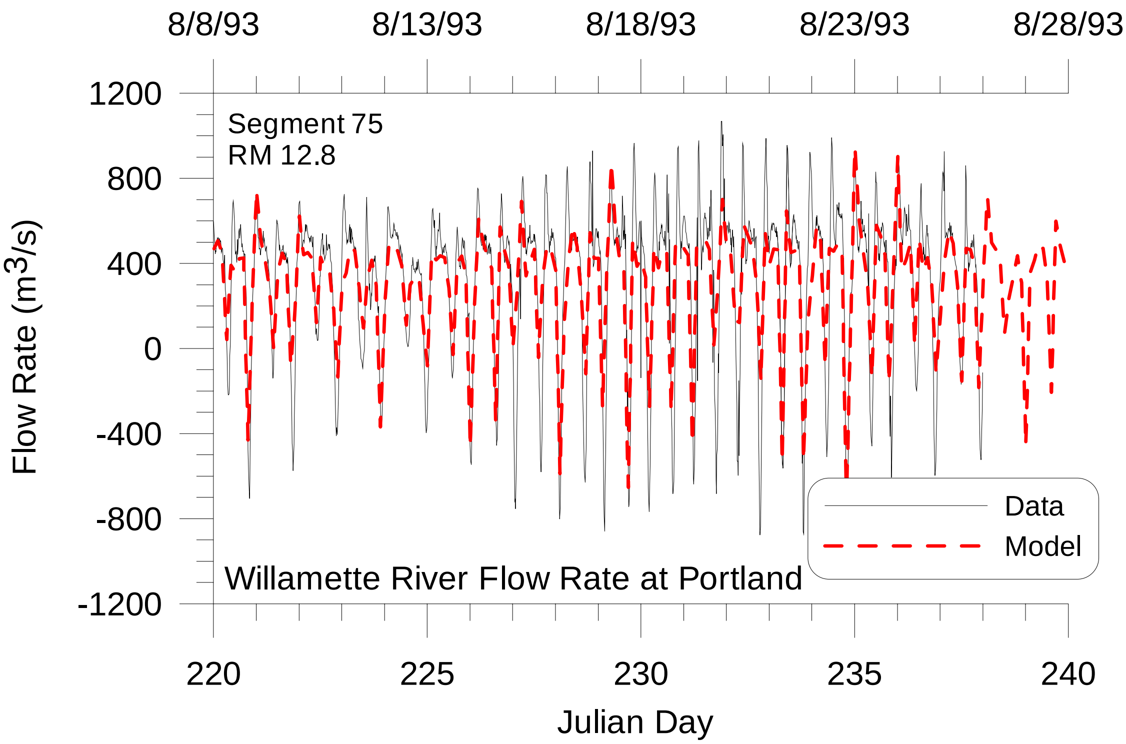

Figure 6. Model flow predictions versus data during a 20-day period during 1993 at Portland.

<u>Temperature Calibration:</u> Model calibration for temperature also depended on good upstream boundary conditions and meteorological data. Grab sample and continuous temperature data were available from 7 sampling sites on the Willamette River and 8 sampling sites on the Columbia River. Typical average mean error for temperature predictions was 0.3-0.9°C. Model temperature predictions from a single station were compared with 1998 continuous data in Figure 7. Because of the short residence time within the model domain, the development of accurate boundary conditions was essential for good temperature calibration.

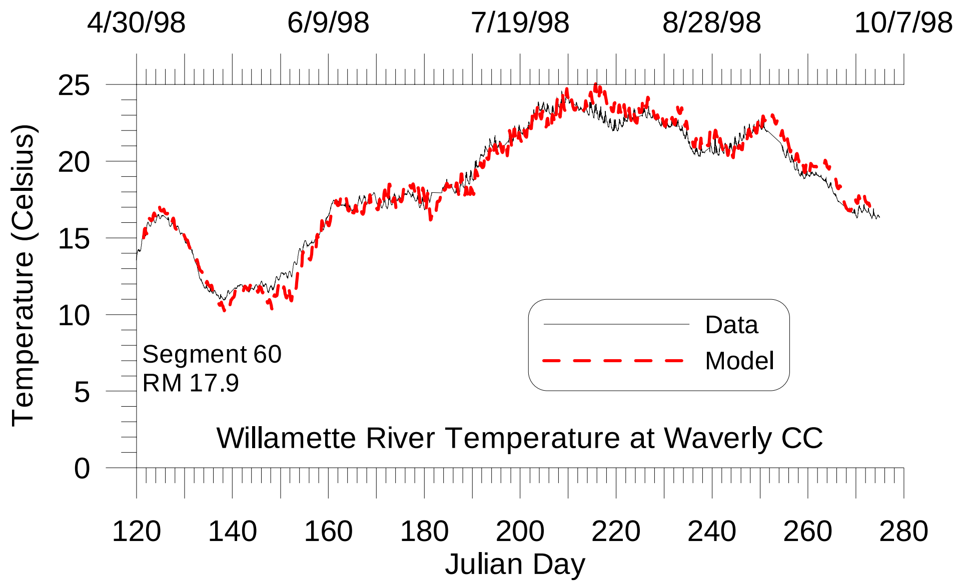

Figure 7. Model temperature predictions compared with continuous data in the Willamette River.

Water Quality Calibration: Water quality field data were obtained from the City of Portland, Bureau of Environmental Services, the US Geological Survey and the Oregon Department of Environmental Quality STORET program to compare with model predictions. There were water quality data available for 13 sites on the Willamette River and 2 sites on the Columbia River. The model was calibrated to water quality constituents such as dissolved oxygen, pH, chlorophyll a, ortho-phosphorus, total phosphorus, ammonia nitrogen, nitrate nitrogen, dissolved organic carbon and total organic carbon. Boundary conditions, algae growth rates, reaeration equation, and sediment oxygen demand were particularly important for model calibration. Zeroth order sediment oxygen demand was set to 1.4 g/m^2 in segments above Willamette Falls and 1.8 g/m^2 for segments below. These values were based on measurements made in 1994 by the U. S. Geological Survey (Caldwell and Doyle, 1995). The rearation equation applied in the model was the Thomann and Fitzpatrick (1982) estuary equation where the rearation K_a (d^{-1}) was calculated using:

$$K_a = \frac{0.728W^{0.5} - 0.317W + 0.0372W^2}{H} + 3.93\frac{\sqrt{U}}{H^{1.5}}$$

where U (m/s) was the water velocity, W (m/s) was the wind velocity, and H (m) was the depth. A reaeration equation appropriate to estuaries equation was chosen because the Lower Willamette River is tidally influenced. An algae maximum growth rate of 2.4 d^{-1} was used for model simulation years 1993, 1994 and 1997 and a maximum growth rate of 2.3 d^{-1} was used for 1998 and 1999.

Continuous and grab sample dissolved oxygen data were compared with model predictions for the Willamette River site St. John's Railway Bridge (RM 6.8) in Figure 8. Comparisons of model predictions and continuous and grab sample field data of pH in 1999 at the Willamette River site Waverly Country Club (RM 3.1) were shown in Figure 9. The model tracked well the variation in grab sample data.

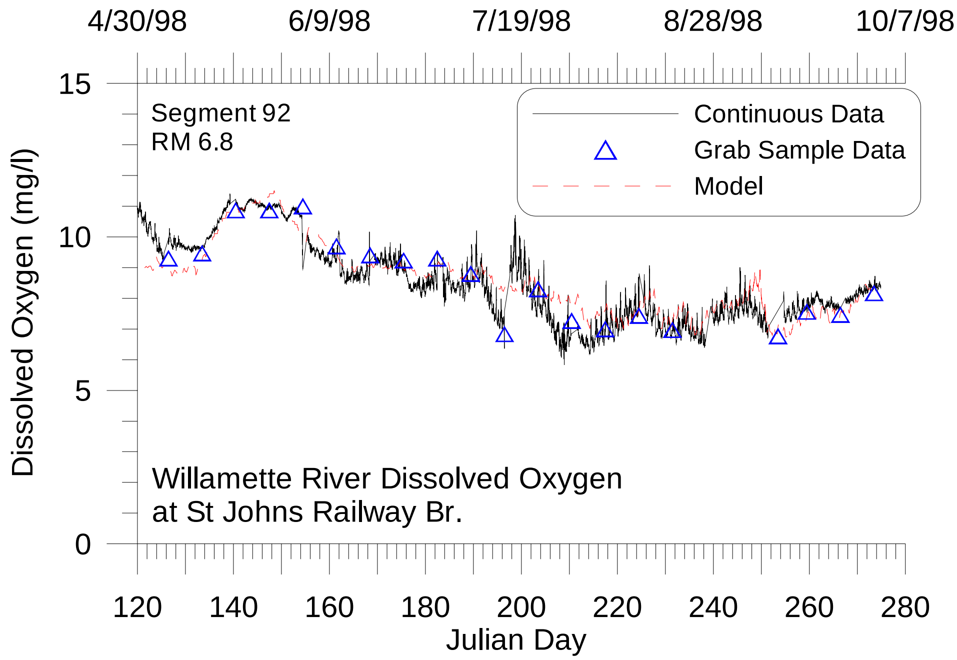

Figure 8. Comparison between model predicted dissolved oxygen concentrations and data for the Willamette River at St. Johns Railway Bridge (RM 6.8) during 1998.

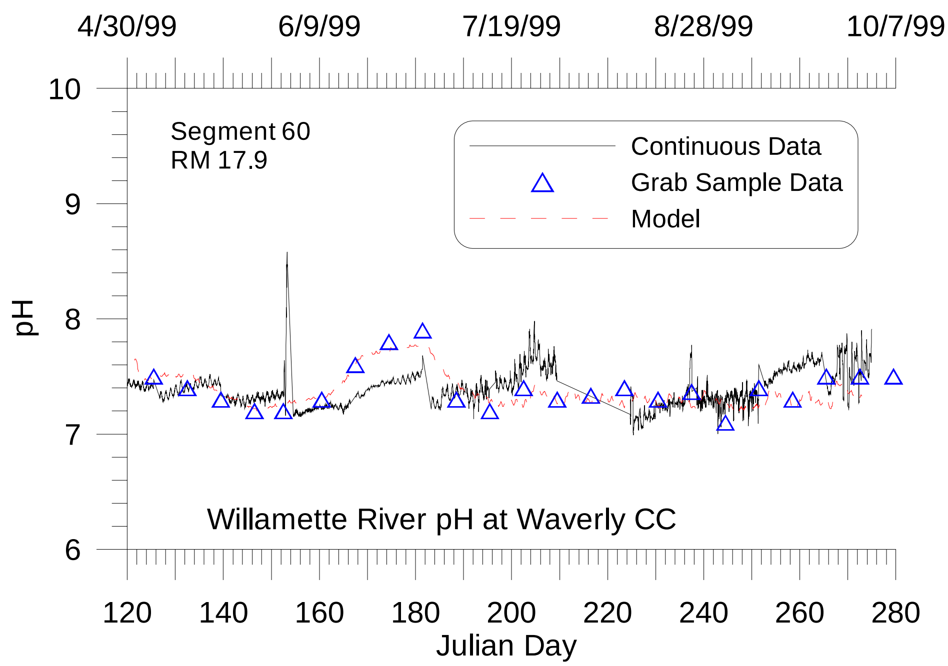

Figure 9. Comparison between model predicted pH and data for the Willamette River at Waverly Country Club (RM 17.9) during 1999.

SUMMARY

A CE-QUAL-W2 Version 3 model (Cole and Wells, 2000) was developed to model the Lower Willamette River in order to assess the impact of the wastewater treatment plant discharges on water quality. The model was set-up for the summer periods (May 1-October 1) of 1993, 1994, 1997, 1998, and 1999. The model boundaries on the Columbia River extended from the Beaver Army Terminal (a downstream head boundary condition) to Bonneville Dam. On the Willamette River they included the confluence with the Columbia River to Canby Ferry at RM 35. A more extensive description of model set-up and calibration is available in Rodriguez et al. (2001) and Berger et al. (2001). The model was compared to hydrodynamic field data (water level and flow rate data), temperature data, and water quality data (dissolved oxygen, chlorophyll a, pH, PO_4-P, NH_4-N, NO_3-N, TKN, TOC) at various stations in the Willamette and Columbia Rivers.

Model calibration showed that in general the model reproduced the hydrodynamics and water quality well during the May-October period despite the fact that many dynamic storm water dischargers were not used in the model. A summary of model errors in the Lower Willamette was shown in Table 2.

Table 2. Typical model errors in the Lower Willamette River.

Parameter	Typical Average Mean Error in the Lower Willamette River	Typical range in variable
Water level, m	0.1-0.25 m	±1.1 m
Flow rate, m^3/s	20 –130 m^3/s	1200 m^3/s
Temperature, ^oC	0.3-0.9^oC	10-24^oC
Dissolved oxygen, mg/l	0.3-1.0 mg/l	7-10 mg/l
Chlorophyll a, ug/l	2-15 ug/l	5-40 ug/l
pH	0.1-0.3	7-8
PO_4-P, ug/l	5-8 ug/l	20-65 ug/l
Total P, ug/l	10-20 ug/l	40-100 ug/l
Ammonia-N, ug/l	10-25 ug/l	40-100 ug/l
Nitrate-N, ug/l	80-100 ug/l	200-600 ug/l
TKN, mg/l	0.03-0.1 mg/l	0.2-0.4 mg/l
TOC, mg/l	0.3-0.5 mg/l	1-2 mg/l

The temperature and water quality model predictions were very dependent on upstream boundary conditions as evidenced by short travel times from the Canby Ferry to the Morrison Street bridge (from 1-4 days). Also, the ability to reduce model water level and flow rate errors is very dependent on having accurate and precise bathymetry data in the model system.

The following conclusions can be made evaluating regarding the modeling effort:

- Interpolating upstream boundary condition data between field sampling every 2 or 3 weeks made it difficult to predict conditions in the Lower Willamette when the data within the model domain was taken at a higher data frequency. It was recommended that future studies consider the use of continuous water quality monitoring devices (such as temperature, dissolved oxygen, and pH) so continuous boundary condition data can be obtained for the Willamette River
- In the W2 model, one algal type with the same kinetic parameters was used for all the years of record. There is probably a basis for using multiple algal types in the model or different algal growth rate kinetics year-by-year but limited data existed making such an effort difficult.

In general, hydrodynamic and water quality features of the system are well reproduced in the model. The use of the model to postulate impacts of increased BOD mass loadings from point sources would be a reasonable use of the calibrated model. Most improvements in model calibration would probably be based on improving upstream boundary conditions for the model, especially water quality parameters for the Willamette River at Canby Ferry (RM 35).

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