Development of a Laterally Averaged 2-Dimensional Water Quality Model of the Sammamish River

(CE-QUAL-W2 Version 3.2)

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[1] Ed Buchak is now with the ERM Surfacewater Modeling Group (http://www.erm-smg.com/index.html)

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Appendix A. Log-Linear regression approach used to estimate selected model constituent boundary conditions

Appendix B. Model control flags and coefficients

EXECUTIVE SUMMARY

This report describes the progress to date in the development of a dynamic mechanistic water quality model of the Sammamish River using CE-QUAL-W2 (version 3.2). Based on comparisons to available data, the model is most capable of simulating water temperatures, except in the lower portion of the river influenced by the backwater from Lake Washington. The model as currently configured is a suitable tool for evaluating potential influences of riparian shade, groundwater flow restoration/augmentation, and other potential water temperature management actions proposed to improve the temperature conditions for salmon on their spawning migration through the river.

Primarily due to the difficulty of capturing the dynamics of aquatic plant growth in the river, the model does not perform as well for other water quality constituents of interest – particularly dissolved oxygen. The model also does not simulate total and dissolved copper well when compared to the limited amount of data currently available. The poor performance of the model with respect to copper may be due to a number of issues, including poorly defined tributary inputs, large errors in the prediction of total suspended solids, and possible misrepresentation of copper fate and transport processes in the model. Copper is currently modeled as a contaminant associated with inorganic suspended solids. Some studies have suggested that dissolved organic carbon may play a role in copper fate and transport in freshwater aquatic systems.

Further improvements in the model's capabilities will only come with additional data collection and further model testing and development. One critical area to focus on is better quantification of ungauged surface and groundwater inputs, primarily of heat (i.e., temperature), dissolved solids (measured as specific conductance) and nutrients. Groundwater inputs to the river during summer low flow have been identified and gradual longitudinal increases in conductance during summer also provide evidence of direct and indirect (through groundwater fed tributaries) groundwater inputs to the river. These inputs have the potential to be cooler and have higher concentrations of dissolved solids and nutrients. Quantification of aquatic plant biomass and additional water surface profiles would also provide additional data for model testing and improvement. To these ends, a study of the river during low flow was planned and initiated in 2007. The next Sammamish River modeling report will describe the results of this study and present model results and testing based on improvements made in light of the new data.

All models are wrong. Some models are useful.

- G.E.P. Box [as cited by D.M. DiToro (2001) p. 1 of Sediment Flux Modeling]

All models are wrong, but some are useful.

- Box, G (1979) "Robustness in the Strategy of Scientific Model Building", in (eds) Launer, R and Wilkinson, G, *Robustness in Statistics*, cited by Temple, J (1998) "Robustness Tests of the Augmented Solow Model", *Journal of Applied Econometrics*, 361-75).

All models are wrong; the practical question is how wrong do they have to be to not be useful.

- Box and Draper [George Box and Norman Draper, Empirical Model Building and Response Surfaces, John Wiley, 1987, pg. 74]

1.0. INTRODUCTION

1.1 Overview

The King County Department of Natural Resources and Parks developed the Sammamish-Washington Analysis and Modeling Program (SWAMP) and the Green-Duwamish River Water Quality Assessment (GD-WQA) [referred to collectively as the Freshwater Program] to assist regional wastewater capital planning, habitat conservation, salmon recovery, and watershed planning efforts by collecting information and by developing and using a set of scientific tools to better understand the Sammamish-Washington and Green-Duwamish Watershed systems. The Freshwater Program was funded as a wastewater capital project beginning in 1999 and the project was completed in 2006.

The Sammamish-Washington and Green-Duwamish watershed systems cover about half of King County and include all of the Seattle metropolitan area, with the exception of nearshore areas that drain directly to Puget Sound (Figure 1). Three major lakes (Lakes Sammamish, Washington, and Union) connected by the Sammamish River and the Lake Washington Ship Canal and Locks system within the Sammamish-Washington study area have been the focus of long-term limnological investigations for several decades. As part of the Freshwater Program, King County developed hydrodynamic and water quality models of these lakes and the Sammamish River.

This report documents the development of a laterally averaged 2-dimensional water quality model of the Sammamish River – one modeling component of the Integrated Water Resources Modeling System (King County 2004) developed as part of the Freshwater Program. The model selected for this effort was CE-QUAL-W2. The version of the model described in this report is version 3.2.

1.2 Study Area

The Sammamish River study area includes Lake Sammamish – the main source of the river – and four major tributaries and smaller drainages that enter along the length of the river before it discharges to Lake Washington (Figure 2). The total basin drainage area covers approximately 626 km^2 (242 mi^2), including the surface of Lake Sammamish. Lake Sammamish is the largest single tributary basin at 251 km^2 (97 mi^2); again including the lake surface. Big Bear Creek is the largest of the four major tributary basins that drain to the river at 130 km^2 (50 mi^2). The remaining direct drainages to the river include Little Bear, North, and Swamp Creeks with drainage areas of 39, 74, and 64 km^2, respectively. There is also a significant amount of more diffuse drainage, primarily originating from the hills and valley to the west of the river (68 km^2). Although all of the drainages to the Sammamish River have urbanized levels of development (primarily low to medium density development), the Lake Sammamish basin remains almost 60 percent forested (based on 1995 land cover data – excluding the lake surface), albeit primarily second and third growth timber. Among the major stream inflows, Big Bear Creek remains the least developed with 40 percent forest cover based on 1995 data. Little Bear has approximately 34 percent forest cover and North and Swamp Creeks have approximately 20 percent forest

cover. Although a relatively large portion of the river drainage is in unincorporated King County, the river traverses municipal jurisdictions of the cities of Redmond, Woodinville, Bothell, and Kenmore.

Figure 1 Freshwater Program study area.

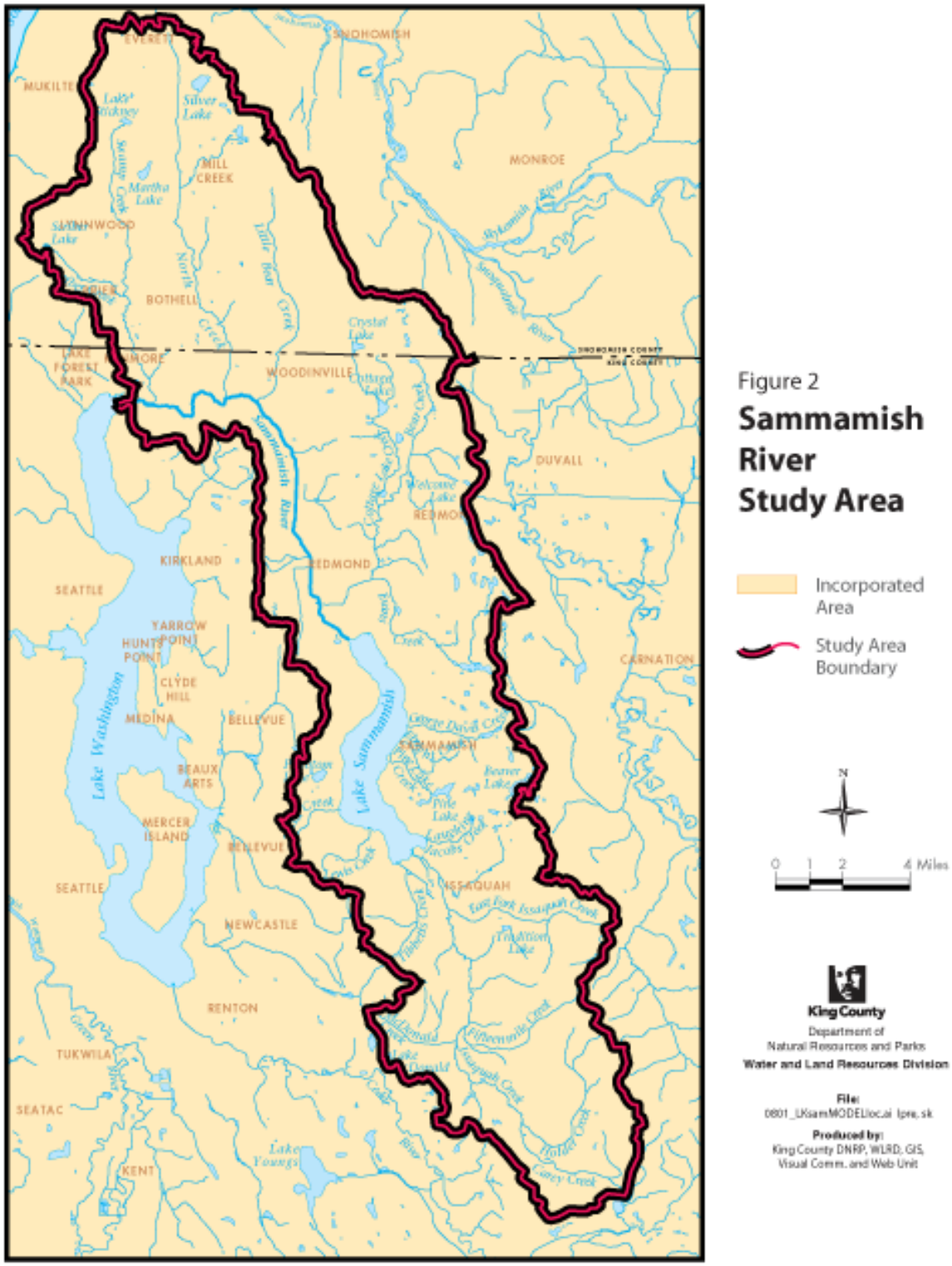

Figure 2 Sammamish River study area.

The inflow from Lake Sammamish at the upstream end of the river is primarily controlled by a broad-crested weir. From the lake outlet to Bothell, the river travels over a broad, low-gradient glacially formed valley generally underlain by pre-Vashon (>15,000 years before present) till, Vashon recessional lacustrine deposits, Vashon recessional sand and gravel, recent flood plain deposits and more recent fill (Liesch et al. 1963). As is typical of this geologic setting, the river historically had a single-channel meandering pattern[2], oxbow lakes, infrequent meander cut-off avulsions, and extensive floodplain wetlands (Collins et al 2003). Over time, these typical Pleistocene valley rivers built their channel (aggraded) through fluvial deposition during flooding events (Collins et al. 2003). Flooding events in these valleys historically spilled water into valley wetlands which remained saturated for long periods of time due to the low valley gradient and low elevation relative to the river banks (Collins et al. 2003). Historically, flooding in the Sammamish valley was further exacerbated by the backwater effect of seasonal high water levels in Lake Washington, which may have inundated much of the valley during the wet season (Stickney and McDonald 1977).

The Sammamish River of the early 1800s has been extensively modified as a result of various human efforts to use the channel for navigation, to utilize the floodplain for agriculture, and to reduce flooding in the Sammamish River valley and Lake Sammamish. Prior to major hydrologic modifications that began in the early 1900s, the river was wider and deeper and generally flowed more slowly due to a relatively small difference in elevation between Lake Sammamish and Lake Washington (Chrzastowski 1983). Ajwani (1956) described the historic river floodplain as a "willow-in[f]ested marsh" (p. 58). During this time, the river was also known as Squak Slough and was navigable over its entire length by shallow-draft steamers and used to float logs and coal barges from Lake Sammamish to Lake Washington (Chrzastowski 1983, Stickney and McDonald 1977). The river was also longer and more meandering prior to major channel modifications during the 20th century. The U.S. Army Corps of Engineers reported that the river was approximately 27 km (17 mi) long as part of a study of the feasibility of constructing a canal and lock system between Lake Sammamish and Lake Washington (U.S. Engineer Office 1891)[3]. This is consistent with the Sammamish River channel defined in the 1893-1895 USGS topographic map (Figure 3). The length of the river currently is about 22 km (13.5 mi) measured between the Lake Sammamish weir and the 68th Ave NE (Juanita Avenue) Bridge at the confluence with Lake Washington in Kenmore, WA.

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[2] Note that King County (2002) indicated on page 2 that the river "contained numerous channels, sloughs, and oxbows from the ***highly braided*** river channel." [emphasis added]. This description is not consistent with the geologic setting or the 1870 cadastral survey map (see: http://riverhistory.ess.washington.edu/duw_puy/glo/framedex.htm), or the 1893-95 USGS topographic map (also see Figure 3).

[3] Note that a historical length of 30 miles was given by Martz et al. (1999) and King County (2002) citing Johnston and Johnston (1976) and Stickney and McDonald (1977). Stickney and McDonald (1977) do state a length of 30 miles on page 7, but McDonald (1979, p. 131) revised the length to 17 miles. No reference to the historical length of the river was found in Johnston and Johnston (1976).

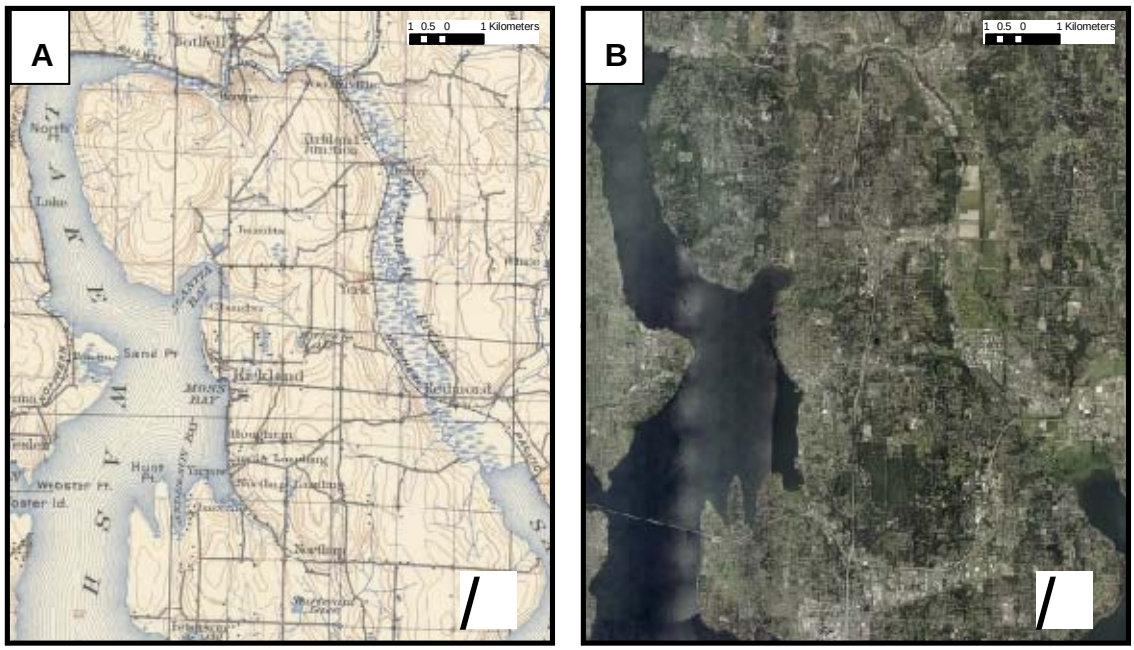


Figure 3 (A) Mosaiced USGS 30 minute topographic maps based on surveys conducted 1893 to 1895 (Snohomish quad that includes the Sammamish River) and (B) 2002 USGS orthophoto mosaic of the Sammamish River study area.

Although early drainage and navigation improvement efforts likely affected the form and function of the river, the most significant modifications occurred as a result of two largely federal-funded navigation and flood control projects. The first major change occurred as a result of the reduction in the mean level and seasonal elevation range of Lake Washington in 1916 as part of the development of the Lake Washington Ship Canal and Lock system, which was officially dedicated on July 4, 1917. This increased the elevation difference between Lake Sammamish and Lake Washington and increased the flow rate of the river and may have reduced flooding in Lake Sammamish to some extent, although no reliable references to effects of the 1916 project on Lake Sammamish water surface levels have been identified at this time.[4] Ajwani (1956) states that the level of Lake Sammamish was only 1.22 m (4 ft) above the level of Lake Washington prior to the lowering of Lake Washington in 1916 by 2.68 m (8.8 ft). However, the U.S. Engineer Office (1891) states that the elevation difference between the two lakes was 2.93 m (9.6 ft). The normal pool elevation difference between the two lakes is currently about 4.0 m. Based on Ajwani (1956), the level of Lake Sammamish probably changed little in 1916 (1.22 m historic difference + 2.68 m drop in Lake Washington = 3.9 m, which is very close to the current difference). However, using the U.S. Engineer Office (1891) elevation difference suggests a drop of about 1.61 m (5.3 ft) in the level of Lake Sammamish in 1916.

[4] Martz et al. (1999) and King County (2002) indicate that the level of Lake Sammamish dropped approximately 6 feet as a result of the lowering of Lake Washington in 1916 citing Chrzastowski (1983), but Chrzastowski (1983) does not describe a drop in Lake Sammamish water levels in 1916.

The second major change resulted from a King County/U.S. Army Corps of Engineers (ACOE) channel dredging, straightening project completed in November 1964 that included construction of a weir at the Lake Sammamish outlet (ACOE 1954, ACOE 1962, ACOE 1965).[5] This project practically eliminated flooding in the Sammamish River valley and reduced maximum flood elevations and seasonal water surface elevations in Lake Sammamish (Figure 4). The weir was modified in 1998 to improve passage for anadromous salmon during low flow.

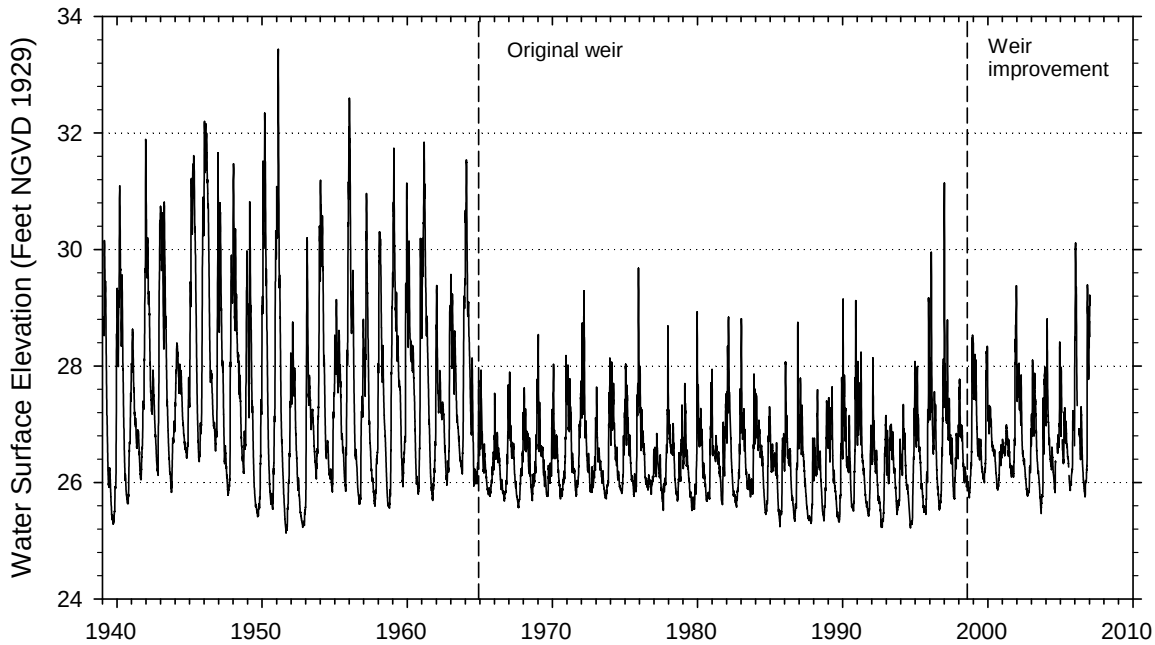


Figure 4 Lake Sammamish daily water surface elevations (USGS gauge 12122000), 1939-2006.

[Note: NGVD 1929 refers to the lake water surface elevation relative to the National Geodetic Vertical Datum of 1929.]

1.3 Background

Concern for water quality conditions in the Sammamish River has been evident at least since the 1950s – primarily with regard to conditions for anadromous salmon and resident trout and human contact recreational use of the river. Ajwani (1956) notes that wastewater from the City of Bothell was a major source of contamination to the river and Lake Washington. As part of the creation of Seattle METRO and diversion of sewage inputs from Lake Sammamish and Lake Washington in the mid to late 1960s, the Bothell wastewater treatment plant discharge was diverted to Puget Sound in March 1967 (Table 4 in Edmondson and Lehman 1981).

[5] Significant straightening/dredging likely occurred prior to this project (see Ajwani 1956, p. 58). For example, aerial photos from the late 1930s indicate that the channel alignment was already very similar to that of today (Collins et al. 2003, p. 115 - http://riverhistory.ess.washington.edu/duw_puy/glo/framedex.htm)

Between March 1967 and February 1969 an investigation of bacteriological and nutrient conditions was conducted throughout the river to evaluate the potential influence of the Lake Hills wastewater treatment plant (WWTP) on river water quality (Dalseg and Hansen 1969). Although the Lake Hills WWTP did not discharge directly to the river, during high sewer flows, treated wastewater was bypassed to the river rather than routing it to the normal discharge – a sprayfield at the treatment plant site. The Lake Hills WWTP ceased operations in 1973 (pers. comm., Sanders-Meena, C., King County) and is now the location of the Redmond Rowing Club, which sits just above the weir across from Marymoor Park in Redmond.

Dalseg and Hansen (1969) concluded that the treatment plant did not appear to be a significant contributor to indicator bacteria or nutrient levels in the river. However, they did conclude that observed increases in indicator bacteria and nutrients as the river flowed from Lake Sammamish to Washington indicated that the drainages to the river contributed significantly to elevated bacteria and nutrient levels. They cautioned that further residential development in the basin should be properly planned, including complete local sewer service, to provide for adequate sanitary and aesthetic conditions in the river and Lake Washington.

A follow-up study in May 1971 focused on temperature, dissolved oxygen, biochemical and chemical oxygen demand and benthic fauna (Clark et al. 1971). Clark et al. (1971) did not note any water quality concerns with reference to Washington Class A standards, although the timing and duration of their study would have certainly missed the elevated temperature conditions during July (> 19 ^{o}C on average throughout the river in 1967 and 1968) that were evident in the earlier study by Dalseg and Hansen (1969). Clark et al. (1971) did note that the Sammamish River bottom was primarily covered with compact sand, which they considered unfavorable for benthic fauna. The samples collected from 7 locations along the length of the river indicated low abundance (12 to 84 organisms per ft^2) dominated by oligochaetes and chironomids. They also noted "numerous subsurface aquatic plants." Clark et al. (1971) suggested that benthic fauna may have been more abundant in areas of dense aquatic plant growth, but their sampling equipment was unsuitable (Ekman dredge) for collecting samples in those locations.

A summary of water quality in the Green and Cedar-Lake Washington basins in the 1970s indicated concern for nutrient, DO, temperature and fecal coliform levels observed in the river (METRO 1978, p 44). METRO (1978) also noted that non-native Eurasian water milfoil (*Myriophyllum spicatum*) was an emerging problem in the upper river. METRO (1982) highlighted limitations to the use of the Sammamish River for potable and livestock water supply and primary and secondary contact recreation due to elevated fecal coliform bacteria levels.

The most recent comprehensive evaluation of river water quality conducted in the fall of 2001 and 2002 included an evaluation of trace metal and organic contaminant levels in water and sediment to establish baseline water quality conditions for future King County projects, such as use of reclaimed water within the basin (King County 2005a). King County (2005a) concluded that no contaminants were measured at concentrations that would suggest significant adverse effects to aquatic life or human health. This study also noted that benthic fauna diversity was relatively low and dominated by a relatively low number of tolerant organisms – oligochaetes and chironomids (King County 2005a).

Washington State Department of Ecology (Ecology) as part of Clean Water Act Section 303(d) evaluation of available data collected by Ecology, King County, and other local jurisdictions, has determined that river beneficial uses (aquatic life and contact recreational use) are impaired and require establishment of Total Maximum Daily Loads (TMDLs) to remedy low dissolved oxygen, high summer temperatures and elevated fecal coliform concentrations (Ecology's 2002/2004 303(d) list approved by the U.S. Environmental Protection Agency http://www.ecy.wa.gov/programs/wq/303d/2002/2002-index.html).

1.4 Goals and Objectives

The overall goal of the Freshwater Program modeling effort was the development and calibration of receiving water-quality models that could simulate water movement (hydrodynamics) and eutrophication processes and their effects on dissolved oxygen and phytoplankton biomass. The models were also to be developed and calibrated to predict the fate and transport of indicator bacteria and a representative trace metal and organic contaminant.

The specific modeling objectives of the Freshwater Program were to:

1. Simulate existing water and sediment quality conditions in the water bodies of the study area and identify any associated risks to aquatic life (including threatened and endangered species), wildlife, and humans. Model results were to be used to supply data where field data were not available either spatially or temporally.
2. Predict future conditions in the water bodies of the watershed and resulting potential risks to aquatic life (including threatened and endangered species), wildlife, and humans under future development conditions as defined by the King County Comprehensive Plan and Growth Management Act.
3. Predict effects of using reclaimed water in the watershed on existing and future conditions and resulting potential risks to aquatic life (including threatened and endangered species), wildlife, and humans.
4. Assess and revise (as needed) current ongoing monitoring programs using the models to ensure monitoring programs are meeting current and possibly future needs.

1.5 Historical Modeling Review

The Sammamish River has been the focus of water quality modeling efforts since the late 1990s beginning with the development of a temperature model by the Seattle District of the U.S. Army Corps of Engineers (ACOE) using CE-QUAL-W2 Version 2.0 (Martz et al. 1999). Martz et al. (1999) indicated that temperature was likely the most significant limiting factor in the Sammamish River for salmonids. Their model, calibrated to data collected during the summer of 1998, suggested that elevated temperatures in the river could be mitigated to some degree through development of riparian shade along the river. The potential cooling effect of a hypothetical withdrawal of cool bottom water from Lake Sammamish placed at the weir was also evaluated. Martz et al. (1999) recommended additional temperature data collection and development of a CE-QUAL-W2 Version 3.0 model that would better represent the river hydrodynamics.

As a result, the Seattle District ACOE contracted with John E. Edinger and Associates, Inc. (JEEAI) to develop a river temperature model using Version 3.0 of CE-QUAL-W2 – the first public-release version of the model capable of simulating sloping rivers (Buchak et al. 2001, Jain and Buchak 2001, Jain et al. 2000). In addition, a more complete continuous temperature data set was developed for calibration that covered June through September 1999. JEEAI (Buchak et al. 2001, Jain and Buchak 2001, Jain et al. 2000) also used the calibrated model to evaluate various temperature management scenarios that included reducing surface water withdrawals, augmentation of existing groundwater inflows, and development of riparian shade. As in the work of Martz et al. (1999), JEEIA (Buchak et al. 2001, Jain and Buchak 2001, Jain et al. 2000) focused their evaluation on short-term worst-case conditions – primarily July 1998, which was then considered to be the warmest month on record for the Sammamish River.

The temperature model developed by JEEAI was improved and set up to perform long-term simulations for a larger number of management scenarios, including combinations of some of the options considered (King County 2002, Appendix B). The interested reader is referred to King County (2002, Appendix B) for details regarding the temperature management application of the model. The version of the model described in King County (2002, Appendix B) – CE-QUAL-W2 Version 3.0 – provided the basis of the model described in this report.

2.0. MODELING APPROACH

In theory, modeling should be an iterative approach that involves initial conceptualization and implementation based on management information needs and available data and resources followed by testing, additional data collection and model refinement. Ideally, modeling and management decision making would be a coupled iterative process that allows for additional data collection, model testing, model refinement, and re-evaluation of model results and management decisions based on them. However, the application of models as an aid in management decision making typically requires a more finite project timeline.

A relatively finite timeline was achieved through the following steps:

- Develop new models or select existing models for project application (Existing models were selected)
- Review of model data needs
- Compilation and review of existing data required for model
- Identification of data gaps or additional data needs
- Additional data collection and incorporation of additional data into model
- Selection of periods for model calibration
- Model setup
- Model calibration and testing
- Identification and implementation of possible model refinements
- Final testing and calibration of model
- Integration of receiving water models
- Integration of receiving water models with watershed models

A brief description of each of these steps that is relevant to the development of the Sammamish River model is provided below. Steps involved in application of individual models or integrated models to water quality management decision making are not addressed in this report.

2.1 Model Selection

An existing 2-D water quality model originally developed for the Sammamish River Corridor Action Plan (King County 2002, Appendix B – see above) was selected for development as part of the King County integrated modeling system.

2.2 Available Data Compilation, Review, and Identification of Data Gaps

DeGasperi (2001) reviewed the water quality models' data needs to identify what data would be required to set up and calibrate the Lake Sammamish and Sammamish River models. The available data for Lake Sammamish, the Sammamish River, and tributary locations near the confluences with the receiving waters were also compiled and reviewed. Data gaps and

additional model needs were also identified. With respect to development of a water quality model of the Sammamish River, DeGasperi (2001) recommended collection of additional parameters at tributary boundary conditions for total organic carbon (TOC), dissolved organic carbon (DOC) and chlorophyll *a*. Initiation of additional Sammamish River mainstem routine sampling locations, as well as continuous DO and pH measurements during critical aquatic plant growth periods were recommended for model calibration. Among other specialized studies that were recommended, DeGasperi (2001) recommended assessment of macrophyte/periphyton biomass and coverage, routine synoptic longitudinal temperature profiles and dye tracer/time-of-travel studies. With the exception of these last recommendations, additional parameters and stations were added to the King County sampling program as recommended.

2.3 Additional Data Collection and Incorporation into Model

As additional data and resources become available, they will be incorporated into the models.

2.4 Selection of Periods for Model Calibration

Because the Lake Washington and Lake Sammamish models are set up and calibrated to the available 1995-2003 data, the Sammamish River model has been set up for the same period. However, since only until recently have Sammamish River routine monitoring stations other than the two at the upstream and downstream boundary been available, only more recent 2000 - 2003 (typically monthly) water quality data are used for model testing and calibration. Continuous temperature data collected since 1999 are used in the temperature model calibration. Continuous DO, pH, specific conductance data and temperature data collected during the summer of 2003 (King County 2005b) are also used in model calibration and testing.

2.5 Model Setup

2.5.1 Grid Geometry

The foundation of a numerical water quality model is the specification of the grid geometry. As in all of the previous versions of the CE-QUAL-W2 models of the river, the available cross section survey data as incorporated into the HEC-RAS flood plain model of the river (WEST Consultants 2004, NHC 1991) were used to develop the CE-QUAL-W2 model bathymetry files. Details on the development of the model bathymetry are provided in Section 4.1 below.

2.5.2 Meteorology

Input files of the meteorological forcing in the appropriate units and format were prepared using hourly air temperature, dew point, wind speed and wind direction, and cloud cover reported for Sea-Tac International Airport and solar radiation reported from either the University of Washington or National Oceanic and Atmospheric Administration (NOAA) Sandpoint Facility depending on availability.

2.5.3 Upstream Boundary Condition

The upstream river model boundary is defined by the lake discharge rate and lake outlet water quality. Daily Lake Sammamish outflow was specified using a combination of gauge observations and a lake stage-discharge relationship developed for the weir at the lake outlet. Hourly lake outlet temperatures were developed from a combination of continuous hourly observations made just above the weir and Lake Sammamish CH3D hydrodynamic model predictions for the outlet (see King County 2008). The quality of the lake outflow was derived from historical water quality monitoring data collected in the lake near the outlet (Station 0625) and at a station just below the weir in Marymoor Park (Station 0486). Details regarding the available data and methods are provided in Section 4 below.

Continuous monitoring of DO, pH, specific conductance and temperature was conducted at a number of locations during the summer of 2003, including a location in the lake outlet (Redmond Rowing Club dock) above the weir (King County 2005b). The available continuous data were used to establish hourly upstream boundary conditions for the summer of 2003.

2.5.4 Tributary Boundary Conditions

The current version of the Sammamish River model includes 4 discrete tributary inflows (Big Bear, Little Bear, North, and Swamp Creeks) and a distributed inflow. Distributed inflow is intended to account for ungauged surface and/or groundwater inputs to the river.

Input files of tributary flow and temperature in the appropriate units and format were prepared using available continuous temperature monitoring and gauging data (hourly) and HSPF models of hourly average flow for un-gauged periods or periods of missing data. Periods for which continuous temperature data were unavailable were filled using a simple zero-dimensional dynamic temperature model calibrated for each tributary to the available temperature records. This is the same approach used to develop the long-term tributary temperatures for the version of the model used to evaluate the temperature management scenarios described in the Sammamish River Corridor Action Plan (King County 2002, Appendix B).

Tributary water quality conditions were specified as daily average concentrations using a combination of observed data and regression models for a subset of constituents. Available routine monitoring data are available for all 4 major tributaries as far back as 1986 for most constituents. Constituents that have not been observed to strongly fluctuate in response to rainfall runoff (i.e., dissolved constituents) were specified on a daily basis by linear interpolation of observed (typically monthly) data. A few parameters that show a clear rainfall runoff response (primarily particulate or particulate associated constituents) were specified on a daily basis using regression equations that included daily flow variables and seasonality in the equation (see Section 4 for more details).

Continuous monitoring of DO, pH, specific conductance and temperature was conducted at a number of locations during the summer of 2003, including a location at the mouth of Big Bear Creek (King County 2005b). The available continuous data were used to establish hourly tributary boundary conditions in Big Bear Creek for the summer of 2003.

2.5.5 Downstream Boundary Condition

The lower portion of the river responds hydraulically to changes in the water surface elevation of Lake Washington (typically referred to a backwater condition). This behavior is analogous to the response of a riverine estuary to changes in tidal elevation; with the exception that the density-driven circulation in the Sammamish River is primarily a function of temperature rather than salinity.

Due to this backwater condition, the downstream boundary of the model is set up as a head boundary condition, which is essentially a time series of elevation changes in Lake Washington. Daily Lake Washington water surface elevation changes provided by the Seattle District ACOE are used to specify the downstream head for the modeling period 1995-2003.

Time-varying temperature and water quality constituent profiles must also be specified at the downstream boundary. The routine Lake Washington profile monitoring data (typically monthly to twice monthly in summer) from Station 0804 were used to specify daily downstream boundary constituent concentrations using linear interpolation.

2.6 Model Testing and Calibration

Once the model boundary conditions were established, the model was executed to simulate each year and model predictions were compared to the available data.

A number of model error statistics were computed and aggregated by parameter, season, and location to evaluate the spatial and temporal prediction capability of the model. Scatter plots (including correlation coefficients) and cumulative distribution plots comparing model predictions (*P*) and observations (*O*) were also prepared. Model error statistics used to evaluate model performance are summarized below.

$$ME\,(Bias) = \frac{1}{N}\sum_{n=1}^{N} P_n - O_n \quad \text{(bias or mean error)}$$

$$\text{AME} = \frac{1}{N}\sum_{n=1}^{N} \left|P_n - O_n\right| \quad \text{(absolute mean error)}$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} \left(P_n - O_n\right)^2} \quad \text{(root mean square error)}$$

$$SE(e) = \sqrt{\frac{1}{N}\sum_{n=1}^{N} \left(P_n - O_n\right)^2 - ME^2} \quad \text{(standard error)}$$

$$\text{REM} = \frac{\sum_{n=1}^{N} \left|P_n - O_n\right|}{\sum_{n=1}^{N} O_n} \; x\,100 \quad \text{(relative error of the mean, percent)}$$

2.7 Identification and Implementation of Model Refinements

As a result of model development work to date, a couple of possible model refinements/additions to the Sammamish River model have been identified and include:

- Incorporation of macrophyte simulation capabilities that should be available in late 2007 as part of Version 3.5 of CE-QUAL-W2
- Refinement of constituent fate and transport for copper and any other trace metal and for development of algorithms for the simulation of organic contaminants.

2.8 Integration of Receiving Water and Watershed Models

Integration of the Sammamish River model with the Lake Sammamish and Lake Washington model will require the translation of outputs from lake and watershed models into river model inputs. Specifically, output of temperature from the Lake Sammamish CH3D model (and flow if predicted by a modified model) and water quality concentrations from the Lake Sammamish CE-QUAL-ICM water quality model will need to be translated into the input file formats used by CE-QUAL-W2. In order to integrate the Sammamish River model with the Lake Washington models, CE-QUAL-W2 river model output will need to be translated into Lake Washington CH3D and CE-QUAL-ICM model inputs.

Integration of the HSPF watershed models with the receiving water models will require translation of the flows and constituent loads or concentrations into the appropriate input formats for each model. Translation between the HSPF model constituents and CE-QUAL-W2 state variables will also be required.

As part of the Freshwater Program, an Integrated Water Resources Modeling System (IWRMS) has been developed to facilitate the integration of these models (King County 2004). Initial testing of this system was conducted in 2007 with Sammamish River basin models (temperature and flow), including Lake Sammamish and the watersheds draining to Lake Sammamish and the Sammamish River (King County unpublished).

3.0. BRIEF DESCRIPTION OF MODEL

CE-QUAL-W2 Version 3.2 is capable of modeling vertical and longitudinal (i.e., upstream/downstream) circulation induced by surface heat exchange, tide (i.e., fluctuations in downstream Lake Washington water surface elevation), wind, density effects (salinity and temperature), freshwater inflows, and turbulence. The CE-QUAL-W2 model was originally developed in the 1970s as the Laterally Averaged Reservoir Model (LARM) by Edinger and Buchak (1975). As the model evolved to handle branching water bodies and estuarine conditions, the model became known as the Generalized Longitudinal-Vertical Hydrodynamics and Transport (GLVHT) model (Buchak and Edinger 1984). The model evolved into CE-QUAL-W2 Version 1.0 with the addition of water quality algorithms by the Water Quality Modeling Group at the U.S. ACOE, Waterways Experiment Station (WES), which was released in 1986 (ACOE 1986). Version 2.0 of the model was released in 1994 (Cole and Buchak 1995). Although Version 2.0 had a number of significant improvements to the previous version, it was still limited to applications to lakes, reservoirs, and estuaries. With the release of Version 3.0 in 2000 (Cole and Wells 2000), it became possible to model rivers, lakes, reservoirs and estuaries as integrated sets of models.

A list of specific capabilities of Version 3.2 of CE-QUAL-W2 (Cole and Wells 2003) includes the following:

- Conservative tracer
- Total dissolved solids
- Ammonia
- Nitrate-nitrite
- Bioavailable phosphorus
- Labile and refractory dissolved organic matter
- Labile and refractory particulate organic matter
- Total inorganic carbon
- Alkalinity
- Dissolved oxygen
- Organic sediments
- User-defined number of
    - Generic constituents (e.g., defined by decay rate and/or settling rate with temperature rate multiplier) primarily for tracer, residence time, any number of indicator bacteria groups
    - Inorganic suspended solids (e.g., to represent various size classes)
    - Carbonaceous biochemical oxygen demand (e.g., to represent various sources)
    - Algal groups (e.g., green, blue-green, and diatom algae)
    - Epiphyton/periphyton groups

- Dynamic topographic and riparian shade algorithms
- Output of parameters derived from the state variables identified above (e.g., pH, total and dissolved organic carbon, total suspended solids, total nitrogen, total phosphorus)

What is not available in Version 3.2 of the model, but that is of interest for model applications to the Sammamish River are algorithms that simulate submerged aquatic plant growth and the effect of aquatic plants on river hydrodynamics. A version of the code that includes macrophytes (and zooplankton) was released to the public as Version 3.5 in late 2007, but was not available when this modeling effort was completed. King County has modified the Version 3.2 code to include a relatively simple approach to account for the increase in bottom friction associated with submerged aquatic plants.

Also not included in Version 3.2 of the model is the ability to simulate the fate and transport of trace metals and organic contaminants that sorb to inorganic or organic solids. The generic constituent algorithm in Version 3.2, which only considered decay, has been modified by King County to include sorption of a specified generic constituent to inorganic suspended solids. This modification allows for the initial development and testing of the simulation of copper fate and transport based on sorption to inorganic solids and settling. The most recent model release of CE-QUAL-W2 (version 3.5) still does not include the capability to simulate the fate and transport of trace metal or organic contaminants.

4.0. SUMMARY OF AVAILABLE DATA FOR MODEL SETUP AND CALIBRATION

4.1 Bathymetric Data

The foundation of a numerical water quality model is the specification of the grid geometry. Cross section surveys were performed in 1984 and 1988 by the Seattle District ACOE at 53 locations (NHC 1991). These data were used to develop a HEC-2 step-backwater model of the river for flood analyses (NHC 1991). A version of this model was obtained from the Seattle District ACOE by JEEAI to develop the bathymetry in the first version of the Sammamish River CE-QUAL-W2 model (Jain et al. 2000). Additional surveying work, especially in the transition zone[6], was recently incorporated into a HEC-RAS version of the model (WEST Consultants 2004). This version of the model was used to develop the bathymetry grid in the version of the model described in this report.

The observed cross section data were extracted from the HEC-RAS model provided by WEST Consultants and processed into Excel tables of average widths at specified elevations relative to the 1929 National Geodetic Vertical Datum (NGVD). A Matlab program was developed to process the cross section data into files formatted for input to the CE-QUAL-W2 model. In general, the processing program starts at the most downstream cross section (currently just downstream of the Juanita Avenue Bridge at the mouth of the river) and determines the average width of sections of uniform length (currently 246.7 m) for a given layer height thickness (currently 0.5 m), starting bottom elevation (currently -0.25 m) and an initial non-sloping section (Waterbody 2) and sloping section (Waterbody 1) with a slope of 0.0002 m/m. As in the previous versions of the Sammamish River model, the grid extends to a location just below the weir and transition zone (see Figure 5 and Figure 6).

The model as currently configured has 82 active segments divided into 2 waterbodies. The original model with 1 waterbody provided by the Seattle District ACOE was separated into 2 waterbodies to better handle backwater conditions in the river and improve the simulation of elevated temperatures observed in the lower river during late summer (see King County 2002, Appendix B). The upstream waterbody is comprised of a single sloping branch containing 63 segments that extend from just below the weir to Bothell. The downstream waterbody contains 19 segments that comprise the portion of the river that is typically affected by summer backwater conditions in the river. Details of the model grid are provided in Table 1.

[6] The transition zone is a short relatively steep reach just below the lake weir that is intended to dissipate flood flow energy before the lake overflow enters the main channel of the Sammamish River.

4.2 Hydrologic Data

In order to set up and evaluate the performance of the model, data are needed to specify upstream and tributary inflows and downstream head boundary elevations. The available data sets and issues addressed to incorporate the data into the model are described below for each component – upstream flow, tributary flow and downstream head. When necessary, date-time was converted to Pacific Standard Time (PST) for model input.

Table 1. Summary of Sammamish River CE-QUAL-W2 model grid statistics.

Total Number of Computational Cells	1312
Number of Surface Cells	82
Layer Thickness (H)	0.5 m (1.64 ft)
Maximum number of layers (K)	16
Segment Length (DLX)	246.7 m (810 ft)
Number of tributary inflow points	4
Number of distributed tributary inflows	2
Number of surface withdrawals	3

4.2.1 Lake Discharge – Upstream River Inflow

Since 1964, discharge from the lake has been controlled by a broad-crested weir. In July 1998 modifications were completed on a low-flow notch added to facilitate passage of spawning salmon during periods of summer low flow. Lake discharge was gauged directly at the weir (USGS 12122010) between 9/75-10/78. Since gauge records were not available for the selected model calibration period, other approaches to estimating outflow from the lake were evaluated. The selected method used a combination of estimates based on gauge data and estimates from a stage-discharge relationship. Gauge estimates were based on daily average Sammamish River discharge at Woodinville (USGS 12125200) adjusted for contributions from Big Bear Creek (King County [KC] 02a) and an estimate of the un-gauged runoff between the lake weir and the Woodinville gauge. Ungauged runoff was estimated as 20 percent of observed Big Bear Creek discharge (based on estimated local runoff area to gauged Bear Creek area). The formula used to estimate lake outflow was:

$$Q_{lake\ outflow} = Q_{Woodivnille} - 1.2\ Q_{BigBear}$$

Outflow was also estimated using a stage-discharge relationships developed for the weir (Figure 7). However, during the process of developing the CH3D-Z model of Lake Sammamish (King County 2008), a hydraulic modeling study confirmed previous suggestions (Hartley 1997, Merkle 1974) that Lake Sammamish stage could be affected by backwater conditions resulting from high flow (and stage) at the mouth of Big Bear Creek (West Consultants 2004). The change in daily lake stage resulting from the January 1997 rainfall event illustrates that the lake

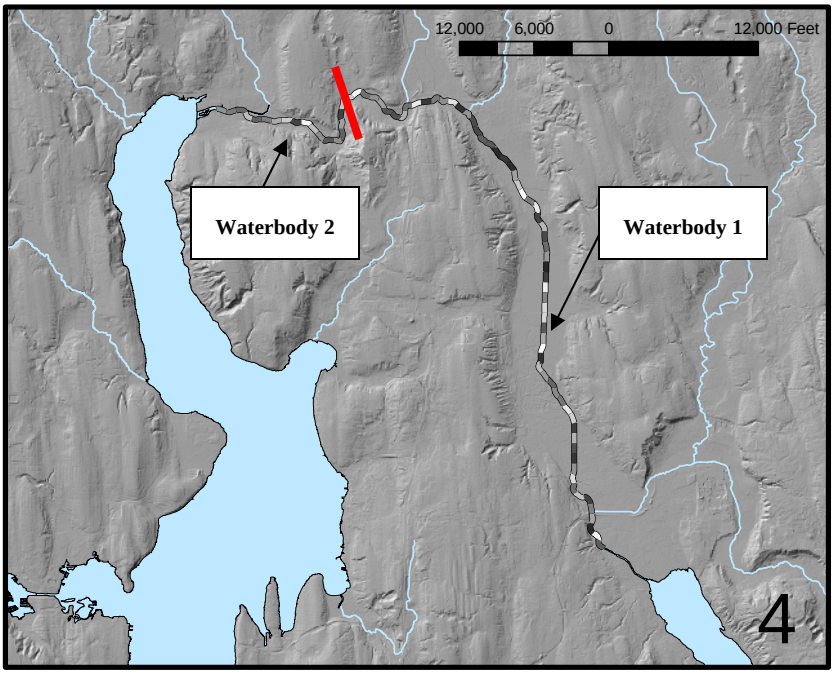


Figure 5 Plan view of Sammamish River CE-QUAL-W2 grid.

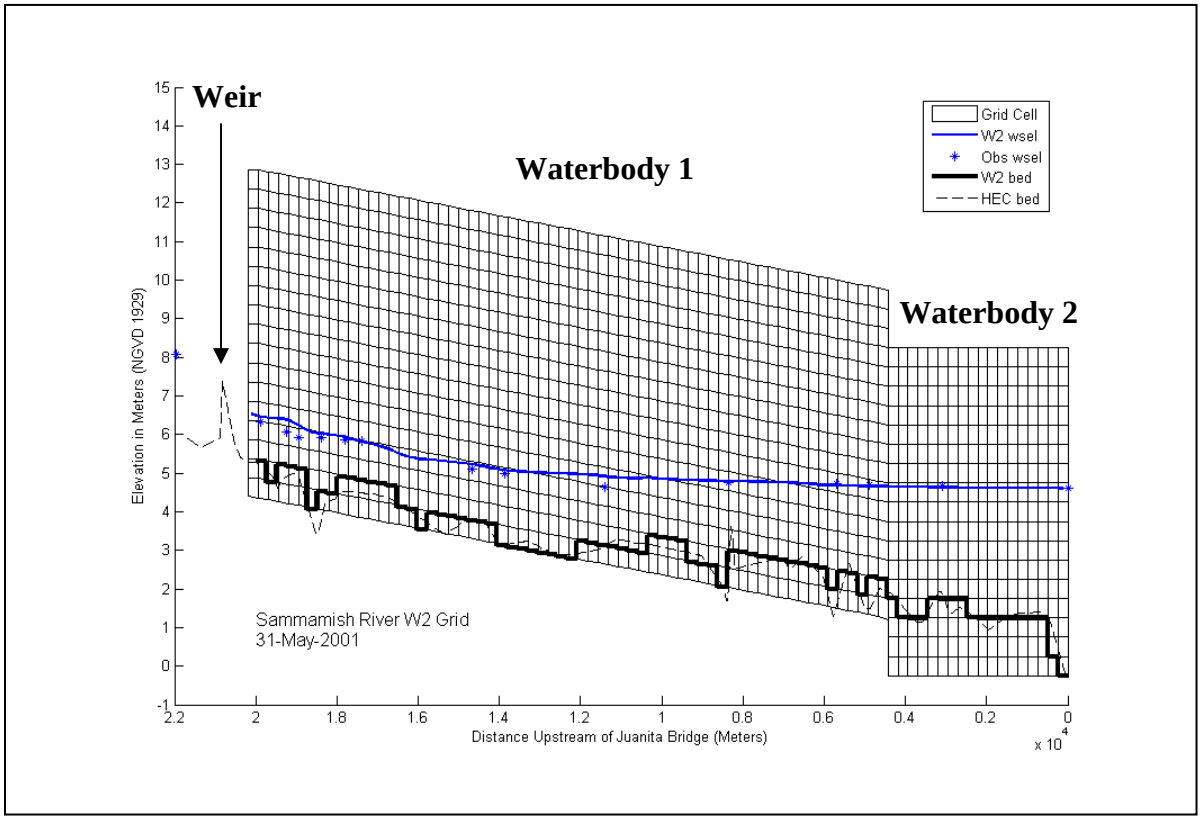


Figure 6 Longitudinal section view of Sammamish River CE-QUAL-W2 grid.

stage-discharge relationship can have a different relationship (i.e., a hysteresis) during the rising and falling limb of the hydrograph (Figure 8). Therefore, a discharge based exclusively on a fixed stage-discharge relationship will over-estimate discharge rates during large storms.

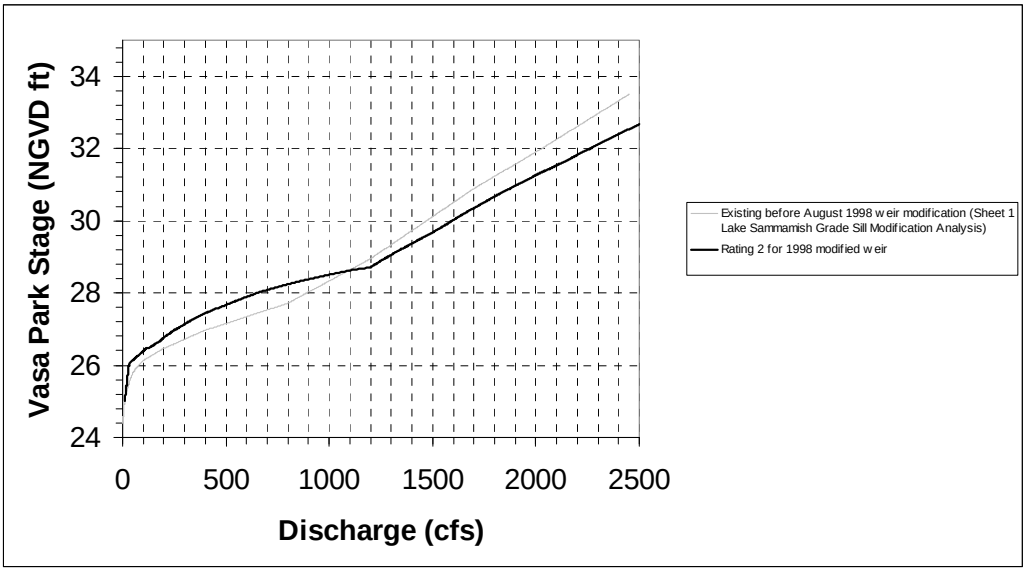


Figure 7 Selected stage-discharge relationships for outflow over the Lake Sammamish weir.

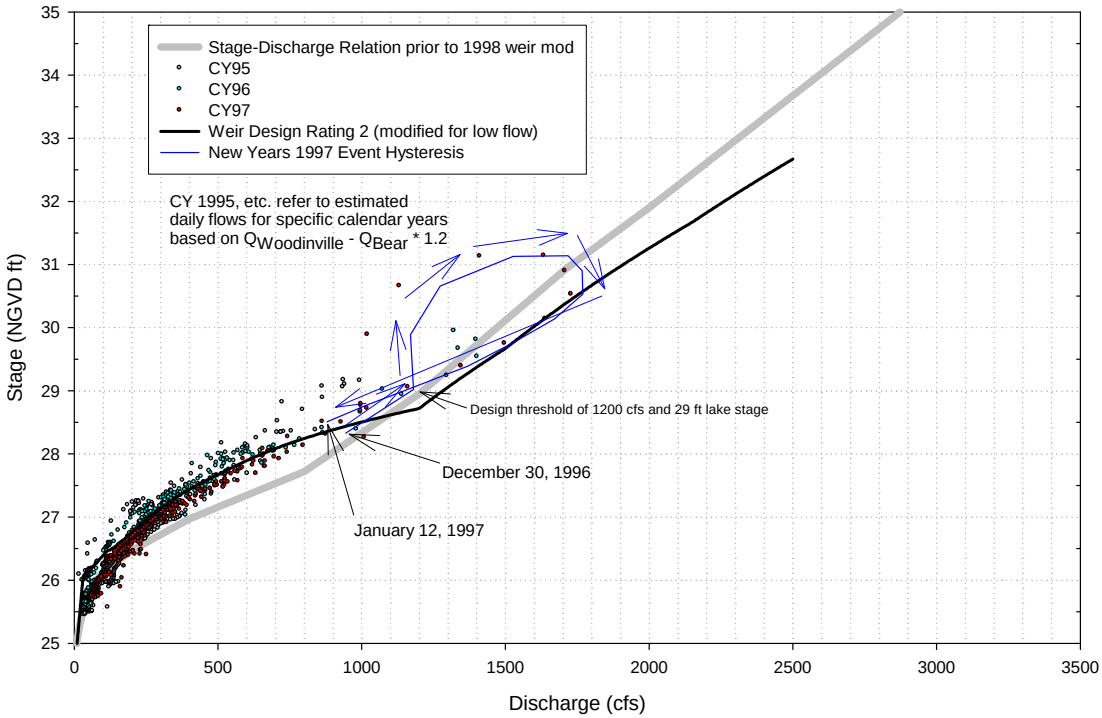


Figure 8 Example of lake outlet stage-discharge hysteresis resulting from New Years 1997 storm.

Figure 9A compares the lake outlet flow rates derived using gauging data and the formula given above to flow rates derived from available stage-discharge relationships for the period before and after the July 1998 weir modification. Available weir (51 m) gauging data collected since 2001 by King County are also shown for comparison. A plot of the difference between discharge estimated using the stage-discharge relationship and the gauged data formula suggests that the winter discharge is overestimated by as much as 600 cfs using the stage discharge relationship – consistent with the observed stage-discharge hysteresis (see Figure 9B). A comparison of the cumulative discharge for the period 1995-2002 (see Figure 9C) suggests that the stage-discharge relationship also tends to overestimate lake discharge in the long term by about 15 percent over the 1995-2002 period.

For this study a threshold of 100 cfs was selected to allow the combination of the two outflow approaches (gauge vs. stage-discharge) over the range of flows that they are most suited for. Below 100 cfs the stage-discharge approach was used and above 100 cfs, the gauge estimate was used. Another possibility for a future version of the model is to use the dynamic Lake Sammamish-Sammamish River HEC-RAS model developed by West Consultants (2004) to better simulate flow at the weir, including the hysteresis. Output from the HEC model could then be used as the input for the Lake Sammamish outlet discharge rate and Sammamish River inflow rate. Testing of this approach is planned in the future.

4.2.2 Tributary Inflow

The U.S. Geological Survey (USGS) and King County have gauged the flows of all 4 major tributaries to the Sammamish River (Table 2, Figure 10). However, with the exception of Big Bear Creek, the records for these tributaries are of more limited duration or do not cover the selected model calibration period. King County has recently developed basin hydrologic models for the entire Sammamish River watershed as part of the Freshwater program. Four separate models representing the major tributaries and a model representing the ungauged areas along the river not necessarily represented by a discrete channel were developed for the basin (King County in progress-see “Modeling” links at http://www.kingcounty.gov/environment/watersheds/green-river/watershed-quality-assessment.aspx.

Modeled runoff from the basins representing overland and subsurface flow from nearshore land areas are distributed to each waterbody – the delineated basin boundaries were used to define which flow files to distribute to each waterbody (Figure 11). This is expected to provide an improvement over the previous approach of multiplying Little Bear Creek flow by a scaling factor of 1.7 based on the relative area represented by the local ungauged catchments and the Little Bear Creek basin (King County 2002, Appendix B; Jain et al. 2000). Observed tributary, lake outlet and HSPF-predicted distributed flows are illustrated in Figure 12. The ratio of HSPF-distributed flow to Little Bear Creek flow (gauged at 30a) is 0.8, which is much lower than the scaling factor based on drainage area ratios. This is due to the low impervious cover and flat terrain represented by the distributed basins that encompass the Sammamish River valley.

The data in Table 3 summarize the estimated mean annual inflows to the Sammamish River used in the model and the basin average runoff yields. Figure 13 shows the relative contribution of

the estimated inflows to the river. Approximately half of the annual inflow comes from Lake Sammamish with the second largest contribution (~20 %) coming from Big Bear Creek.

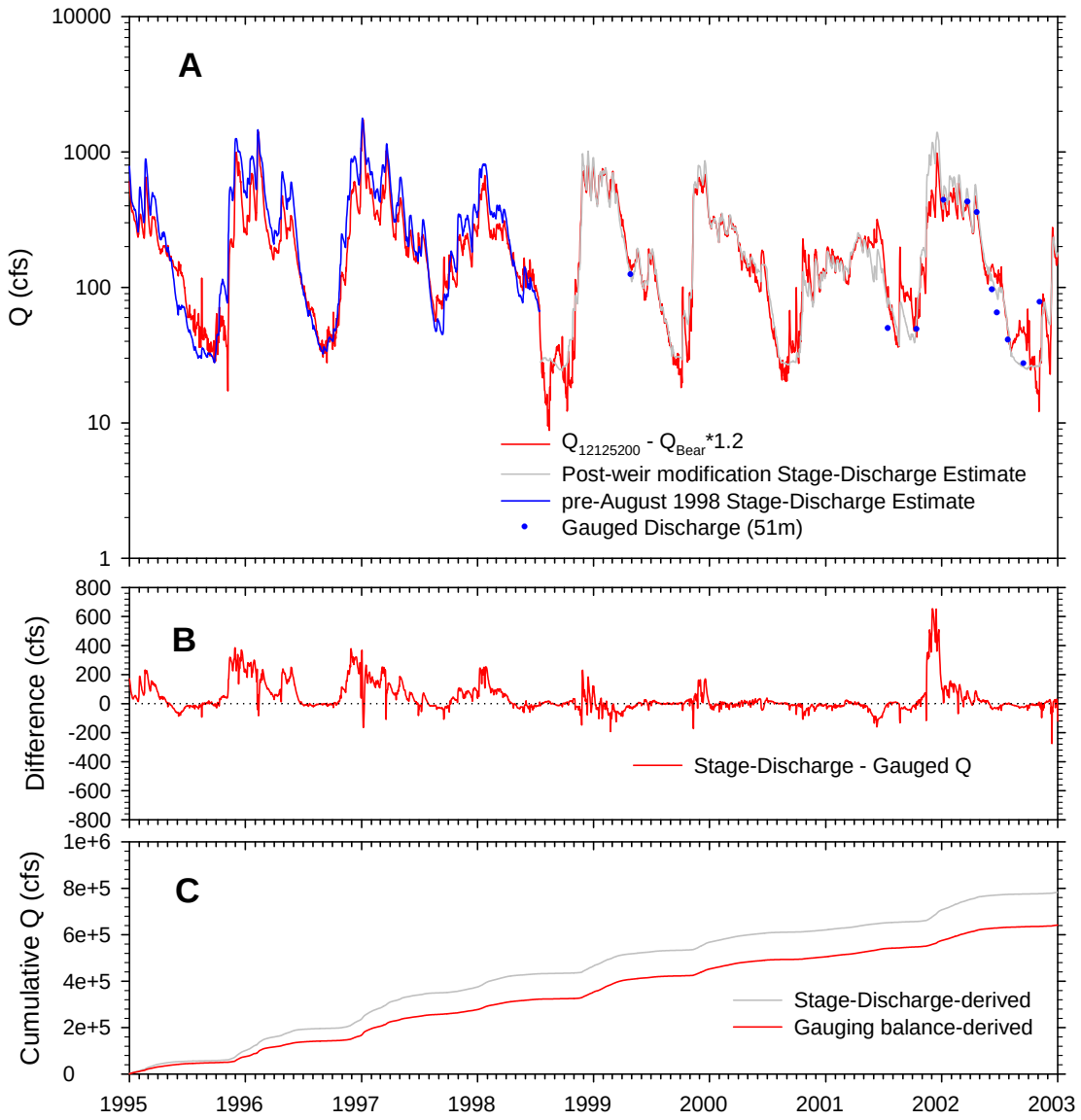


Figure 9 Comparison of Lake Sammamish daily outlet discharge based on outlet gauging balance and available stage-discharge relationships (A), difference between outlet discharge estimated from stage-discharge relationship and gauging balance (B), and comparison of cumulative discharge based on these two methods (C), 1995-2002.

Table 2. Selected stream gauges in the Sammamish River basin.

Site Code	Site Name	Northing	Easting	Date Installed	Date Removed
King County/Snohomish County					
02a	Bear Creek @ Mouth	248836	1326557	10/1/1987	Active
30a	Little Bear Creek at State Route 202	278818	1312910	10/6/1998	Active
45Nc [a]	North Creek @ County Line (Snohomish Co.)	287586	1307217	5/21/1988 [a]	Active
56b	Swamp Creek	283182	1293821	10/1/1999	Active
51m	Sammamish River @ Marymoor Weir	242764	1323957	7/18/2001	Active
USGS					
12124500	Bear Creek at Redmond	246735	1325986	6/1/1945	3/23/1987
12125500	Little Bear Creek near Woodinville	278879	1312849	7/1/1945	8/31/1969
12126000	North Creek near Bothell	291682	1305080	7/1/1945	7/12/1973
12127100	Swamp Creek at Kenmore	278874	1295969	10/1/1963	5/8/1990
12126500	Sammamish River at Bothell	279755	1303365	10/1/1939	10/6/1986
12122010	Sammamish River above Bear Creek	242507	1324341	9/25/1975	10/11/1978
12125200	Sammamish River near Woodinville	259536	1318058	2/1/1965	Active

Northing/Easting in State Plane feet, Washington North, North American Datum 1983

[a] Gauge operated by Snohomish County. Available hourly data begin October 1, 1997.

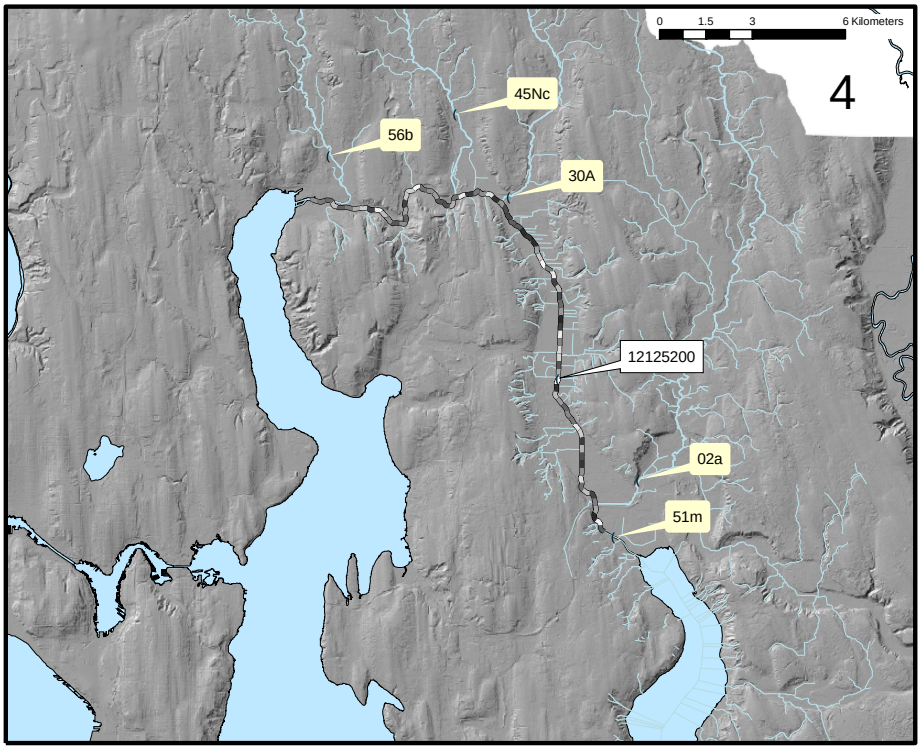


Figure 10 Selected tributary stream and river flow gauging locations.

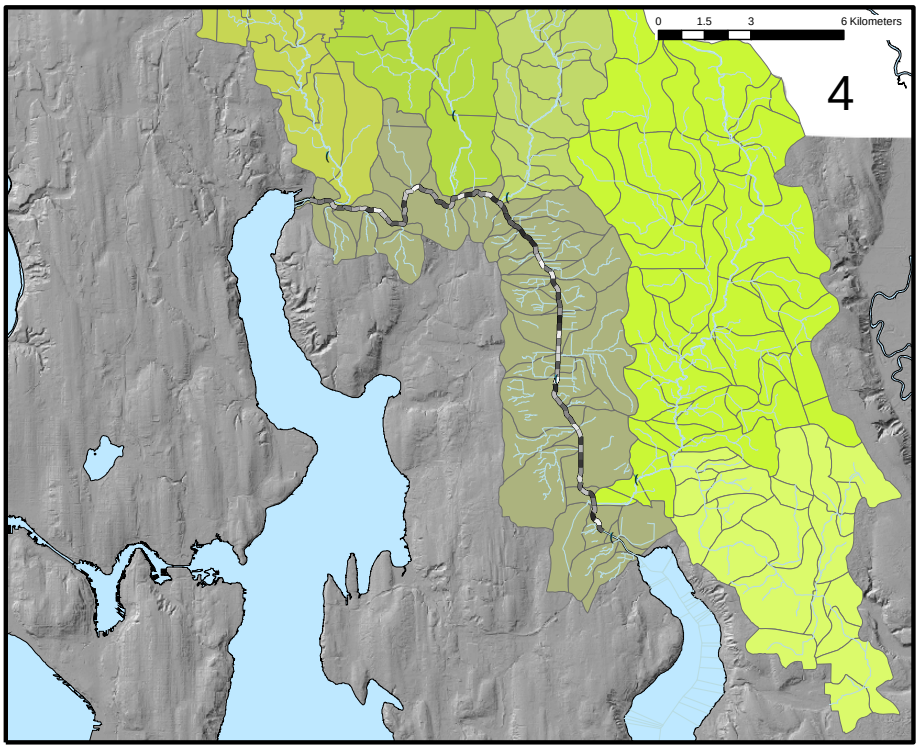


Figure 11 HSPF tributary (green) and distributed basin (brown) model catchments.

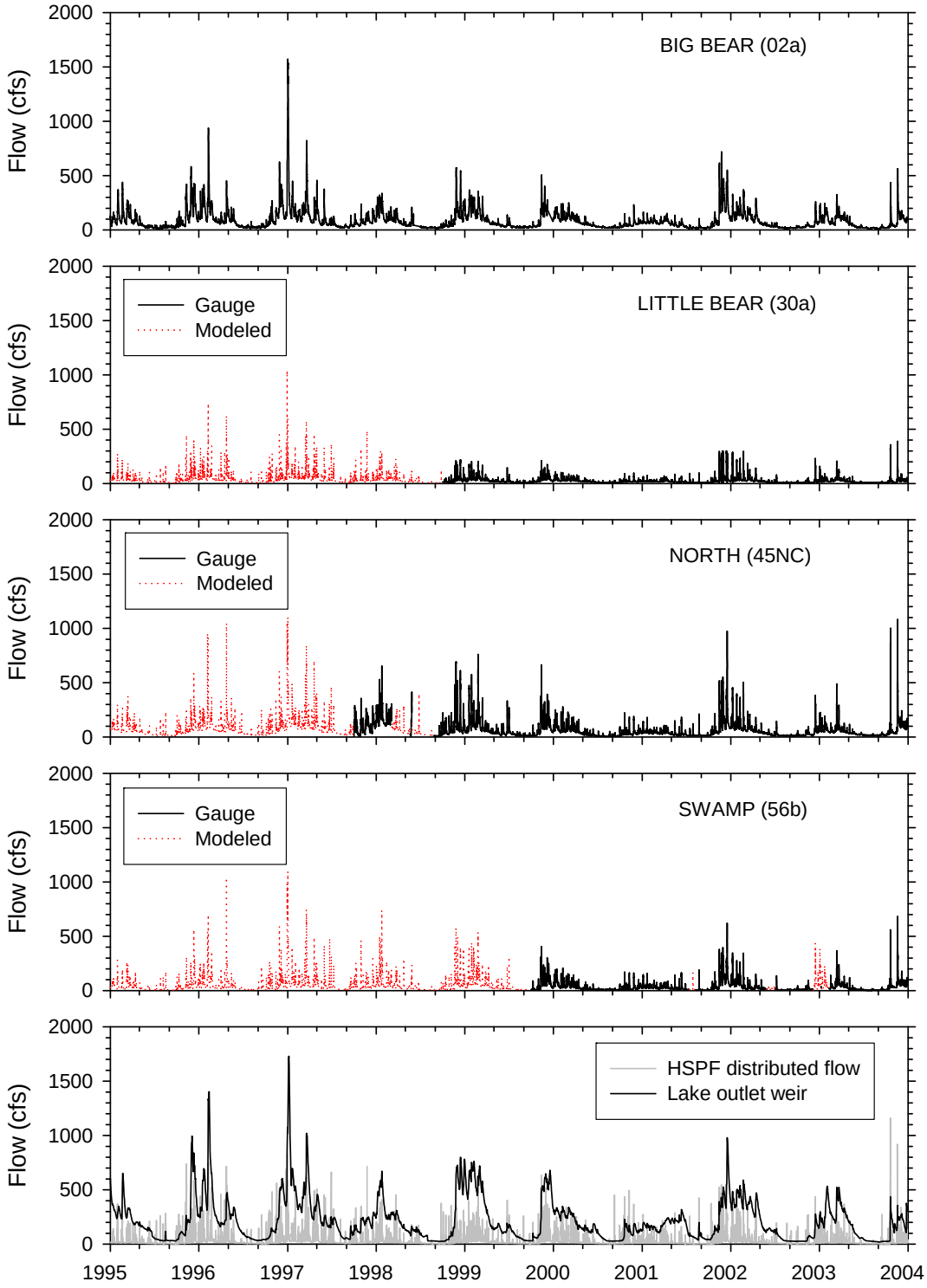


Figure 12 Model flow boundary conditions developed from a combination of gauge records and HSPF models.

Table 3. Estimated annual average inflow and water yield to the Sammamish River, 1995-2003

Basin	Flow		Drainage Area		Yield	
	m3 s-1	cfs	km^2	mi^2	m yr^{-1}	in yr^{-1}
Lake Sammamish	6.03	213	251	96.9	0.76	30
Big Bear	2.46	87	130	50.2	0.6	24
Little Bear	0.79	28	39	15.1	0.64	25
North	1.78	63	74	28.6	0.77	30
Swamp	1.19	42	64	24.7	0.58	23
Distributed	0.62	22	68	26.3	0.29	12

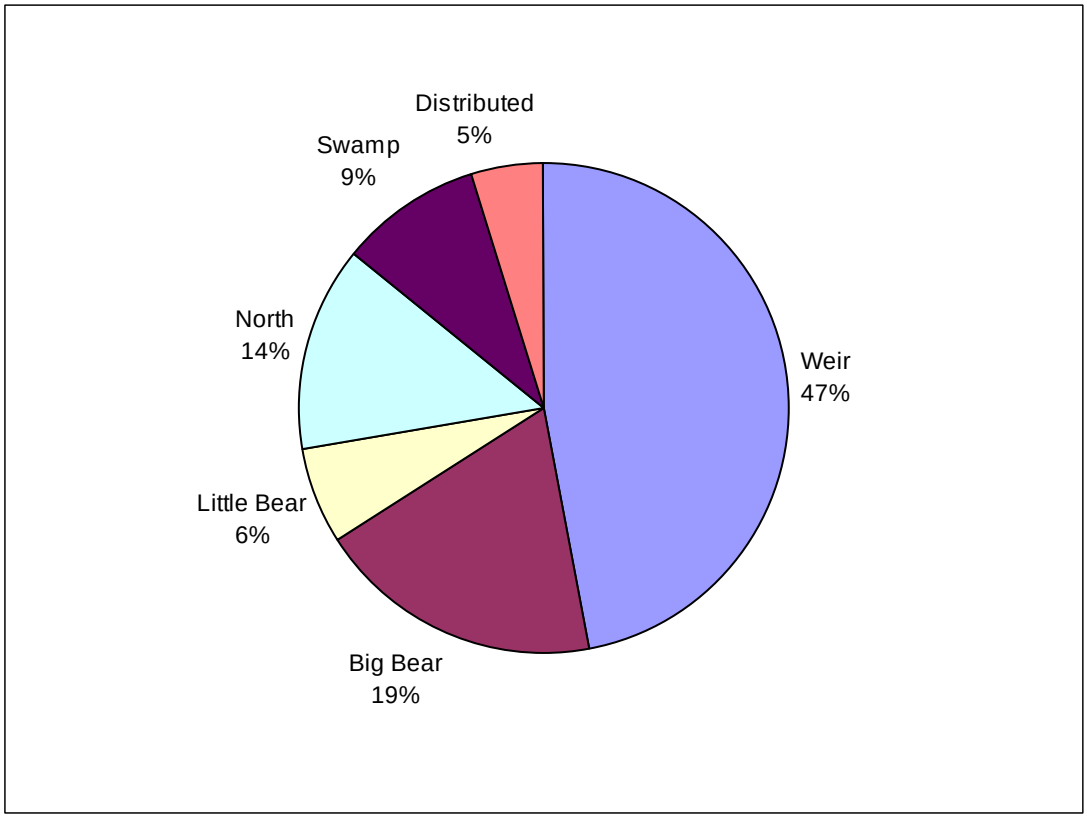


Figure 13 Estimated annual average inflow contributions to the Sammamish River, 1995-2003.

4.2.3 Instream Water Surface Elevations

In the absence of time-of-travel studies for calibration of the model hydrodynamics, periodic measurements of water surface elevations collected at bridge crossings as part of a King County Sammamish Valley groundwater study are available to calibrate the friction factor specified in the model. The spatially varying friction factor controls river velocities and water travel/hydraulic residence time. The available water surface profile data collected in 2001 and 2002 are shown in Figure 14.

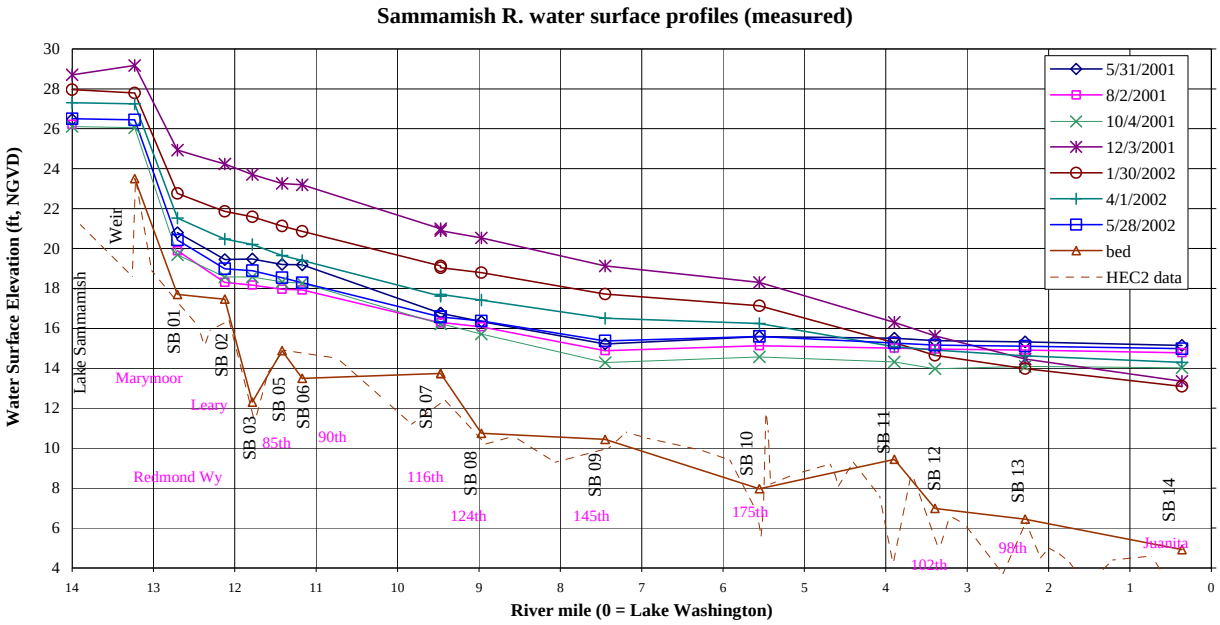


Figure 14 Water surface profile observations of the Sammamish River in 2001 and 2002.

4.2.4 Lake Water Surface Elevations – Downstream Head Boundary Condition

Daily water surface elevation records in feet are available from the Seattle District ACOE for 2 locations in Lake Washington – Kenmore at the north end of the lake near the mouth of the Sammamish River and at the Lake Washington Ship Canal Hiram Chittenden Locks (Figure 15). King County (2002, Appendix B) noted some problems with the Kenmore gauge (a systematic upward trend relative to stage observed at the locks). For this application, the observed stage at the locks is used as the downstream head boundary condition. The vertical datum for these lake stage records is the ACOE datum. The data for the selected model calibration period were converted to model datum (NGVD 1929 meters) using the formula NGVD29_m = (ACOE_ft – 6.82) x 0.3048. Daily stage records for the period 1995-2003 are shown in Figure 16.

Figure 15 Locations of ACOE water surface elevation gauges on Lake Washington (source Seattle-District ACOE http://www.nwd-wc.usace.army.mil/nws/hh/basins/lkwash.html).

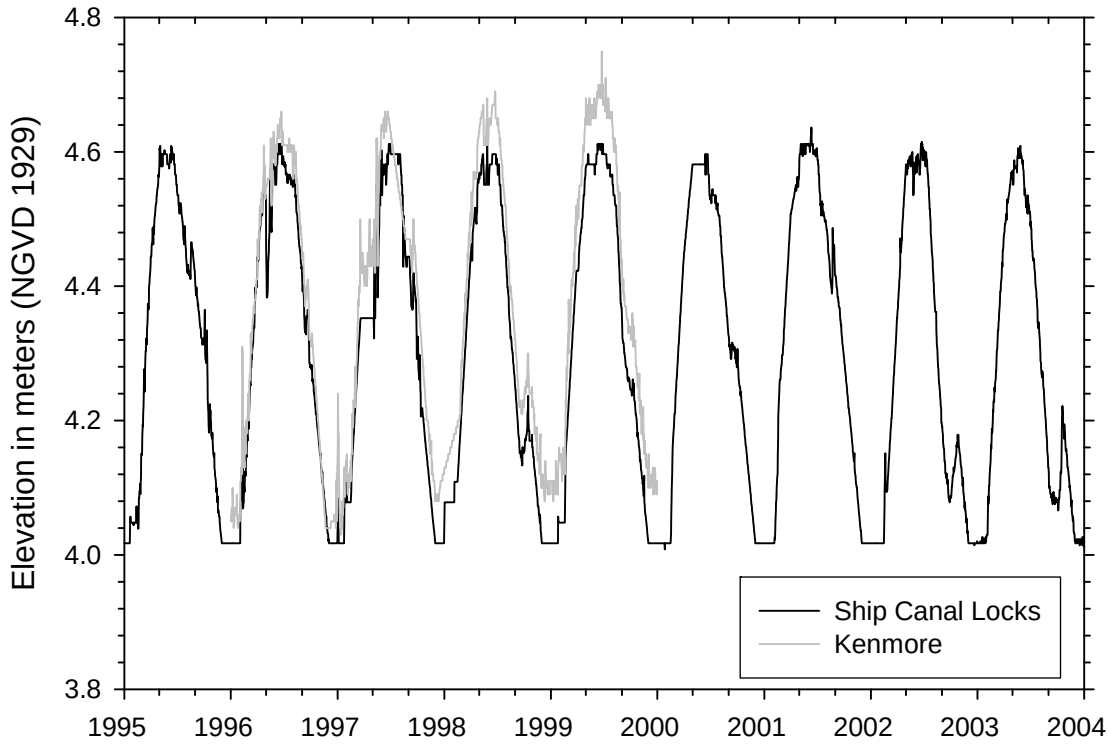


Figure 16 Daily Lake Washington water surface elevation reported by the Army Corps of Engineers, 1995-2003.

4.3 Water Quality Data

The water quality (including temperature) of the lake outflow, the 4 major tributaries, and the river mainstem has been monitored by King County on a routine basis[7] during the period selected for model calibration (Table 4, Figure 17). Continuous (15 minute and hourly) temperature data have also been collected at the lake outlet, the major tributaries and along the river mainstem beginning as early as 1995 at the lake outlet weir (51m), Big Bear Creek (02j), and a location on the Sammamish River near Willows Run Golf Course (51n) (Table 5, Figure 18). Continuous DO, pH, specific conductance, and temperature were recorded during the summer of 2003 at the upstream boundary (Redmond Rowing Club), near the mouth of Big Bear Creek and at several locations along the river mainstem (King County 2005b). The available water quality data for the specification of boundary conditions and model calibration are described below. When necessary, sample collection/recording time was converted to PST.

[7] Monthly grab samples with up to 6 additional wet season and 6 additional dry season grab storm water samples per year (King County 2002).

Table 4. Selected King County routine water quality monitoring locations.

Locator	Description	Northing	Easting	Begin Date	End Date
0625	Lake Sammamish outlet	240581	1326620	2/8/1995	Active
0486	Sammamish River at Marymoor Park	244278	1322276	4/13/1976	Active
0484	Big Bear Creek	246843	1325858	12/21/1971	Active
0450D	Sammamish River below Big Bear	248638	1320337	8/12/2002	1/18/2005
0450C	Sammamish River at NE 124th St	262185	1318042	2/14/2000	Active
0450BB	Sammamish River above Little Bear	278159	1311972	8/13/2002	1/18/2005
0478	Little Bear Creek	278818	1312537	12/2/1971	Active
0450B	Sammamish River above North	279169	1308101	8/13/2002	1/18/2005
0474	North Creek	278813	1307015	12/2/1971	Active
0450A	Sammamish River at Bothell Landing	279449	1302571	2/14/2000	Active
0470	Swamp Creek	278724	1295913	12/2/1971	Active
0450	Sammamish River at Kenmore	278405	1291980	12/2/1971	Active
0804	North end of Lake Washington	275701	1286684	3/31/1981	Active

Northing/Easting in State Plane feet, Washington North, North American Datum 1983

Table 5. Selected King County and ACOE continuous temperature monitoring locations.

Locator	Description	Northing	Easting	Begin Date	End Date
SMR1344	Lake Sammamish – Redmond Rowing Club	241370	1325268	7/27/1999	1/31/2005
51m	Lake Sammamish weir	242764	1323957	8/2/1995	Active
02a	Big Bear Creek	248836	1326557	2/1/1995	Active
02j	Big Bear Creek near mouth	246335	1322055	10/1/1995	Active
BBR004	Big Bear Creek near mouth	246154	1323947	5/31/2000	11/17/2004
51L	Sammamish River at Redmond Railroad Bridge (was SMR1156)	249009	1320373	11/1/2001	Active
RRB (ACOE)		NA	NA	6/1/1999	10/22/1999
51n	Sammamish River at Power Lines	254142	1320107	3/10/1995	Active
116th (ACOE)	Sammamish River at NE 116th St Bridge	NA	NA	6/1/1999	10/22/1999
124th (ACOE)	Sammamish River at NE 124th St Bridge	NA	NA	6/1/1999	10/22/1999
SMR0735	Sammamish River at NE 145th St Bridge	269985	1317445	11/1/2001	10/20/2004
51R	Sammamish River at Woodinville (was SMR0545)	278028	1312006	11/1/2001	Active
30A	Little Bear Creek at SR 202	278818	1312910	10/1/1999	Active
LBR0003	Little Bear Creek near mouth	278234	1312084	11/1/2001	1/31/2005
SMR0458	Sammamish River at I-405	278971	1308136	11/1/2001	10/20/2004
45A	North Creek near mouth (was NCK0008)	279146	1307105	11/20/2000	Active
SMR0255	Sammamish River at Blyth Park	276628	1301796	3/12/2002	8/1/2002
Blyth (ACOE)		NA	NA	6/1/1999	8/25/1999
56b	Swamp Creek	283181	1293821	10/8/1998	Active
56A	Swamp Creek near mouth (was SWP0043)	278594	1295927	1/24/2000	Active
SMR0035	Sammamish River at Juanita Bridge	278416	1291999	10/19/1998	8/1/2002

Northing/Easting in State Plane feet, Washington North, North American Datum 1983

NA = Not available.

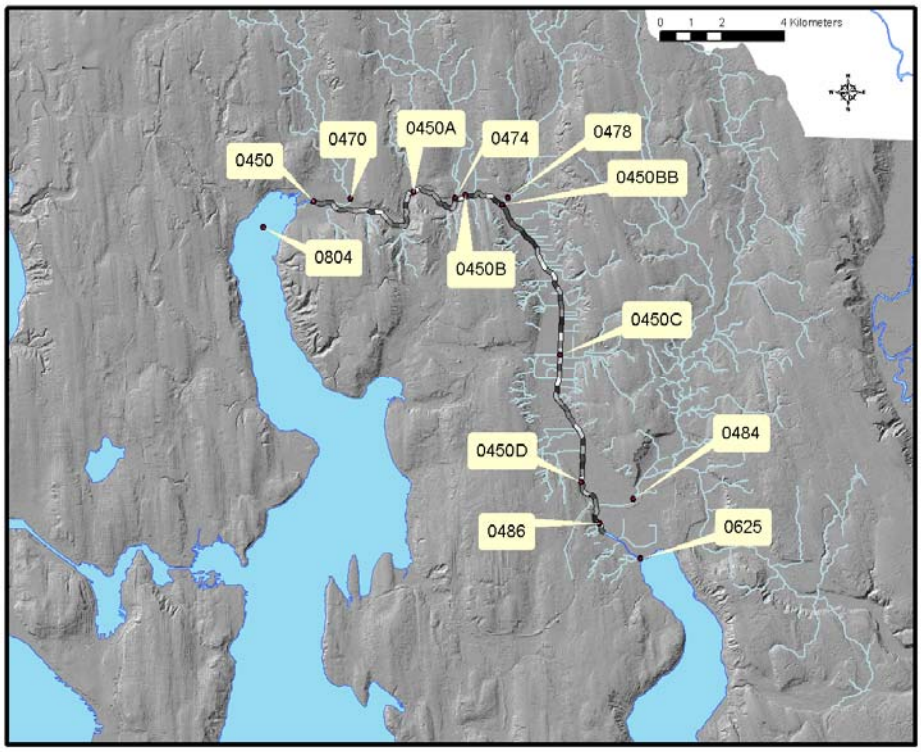


Figure 17 Locations of selected King County routine water quality monitoring stations.

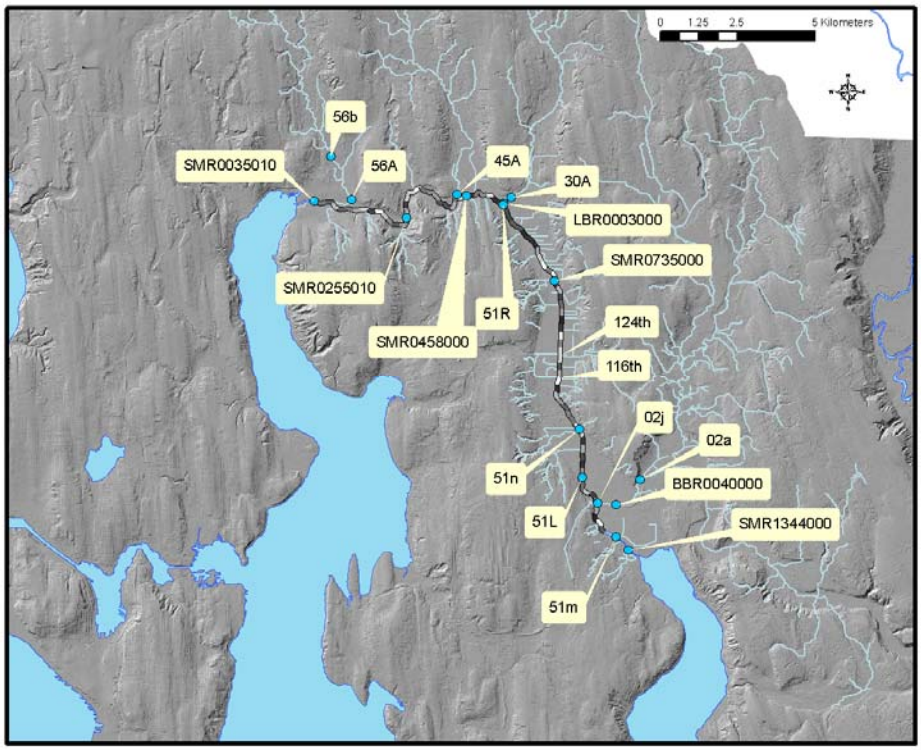


Figure 18 Locations of selected King County continuous temperature monitoring stations.

4.3.1 Water Temperature

In order to develop a dynamic simulation model capable of simulating temperature changes over the course of each day, relatively continuous temperature data are needed. A combination of continuous temperature records and temperature simulation models were used to develop hourly temperature inputs for the period 1995-2003. Continuous temperature measurements made hourly at various locations along the river mainstem were also compiled for use in model calibration. The available data and methods used to fill model input data gaps are described in the following sections.

4.3.1.1 Upstream Boundary

Continuous data collected at the Redmond Rowing Club (SMR1344) and the lake outlet weir (51m) were combined with temperature output from the Lake Sammamish CH3D model (King County 2008) to provide hourly upstream temperature boundary conditions (see bottom panel of Figure 19). The CH3D model provides a reasonably good supplement to the observed data based on comparison to the available observations (see King County 2008).

4.3.1.2 Tributaries

As with the upstream boundary, data gaps in the available continuous temperature records necessitated the use of a model to fill in tributary data gaps over the 1995-2003 simulation period. A simple zero-dimensional dynamic temperature model (commonly called a Response Model) was developed using an explicit heat balance approach. The model included calibration constants for reduction of incoming solar radiation (riparian shade), water depth, groundwater flow, and groundwater temperature. The model was calibrated for each tributary using the available continuous monitoring data. Calibration was generally conducted by incrementally changing various calibration constants until a reasonably small bias and RMSE was achieved. Resulting hourly tributary temperatures used in the model are shown in Figure 20.

Currently, the temperature of the distributed inflow derived from the HSPF model is equivalent to the temperature specified for Little Bear Creek. In the future, a more realistic temperature should be developed using a combination of available groundwater and surface water observations and a regional groundwater model of the Sammamish Valley (King County in progress).

4.3.1.3 In-stream Calibration Data

Continuous temperature data for calibration are available from 9 locations along the river (see Table 5 and Figure 18), including the observations at the Juanita Bridge at the downstream boundary. With the exception of the long-term record at 51n near the Willows Run Golf Course, model calibration data are generally unavailable until the summer of 1999[8] (Figure 20). Periods of

[8] The Seattle District ACOE also collected mainstem temperature data in 1998, but some of these data were of suspect quality and have not been used in this application.

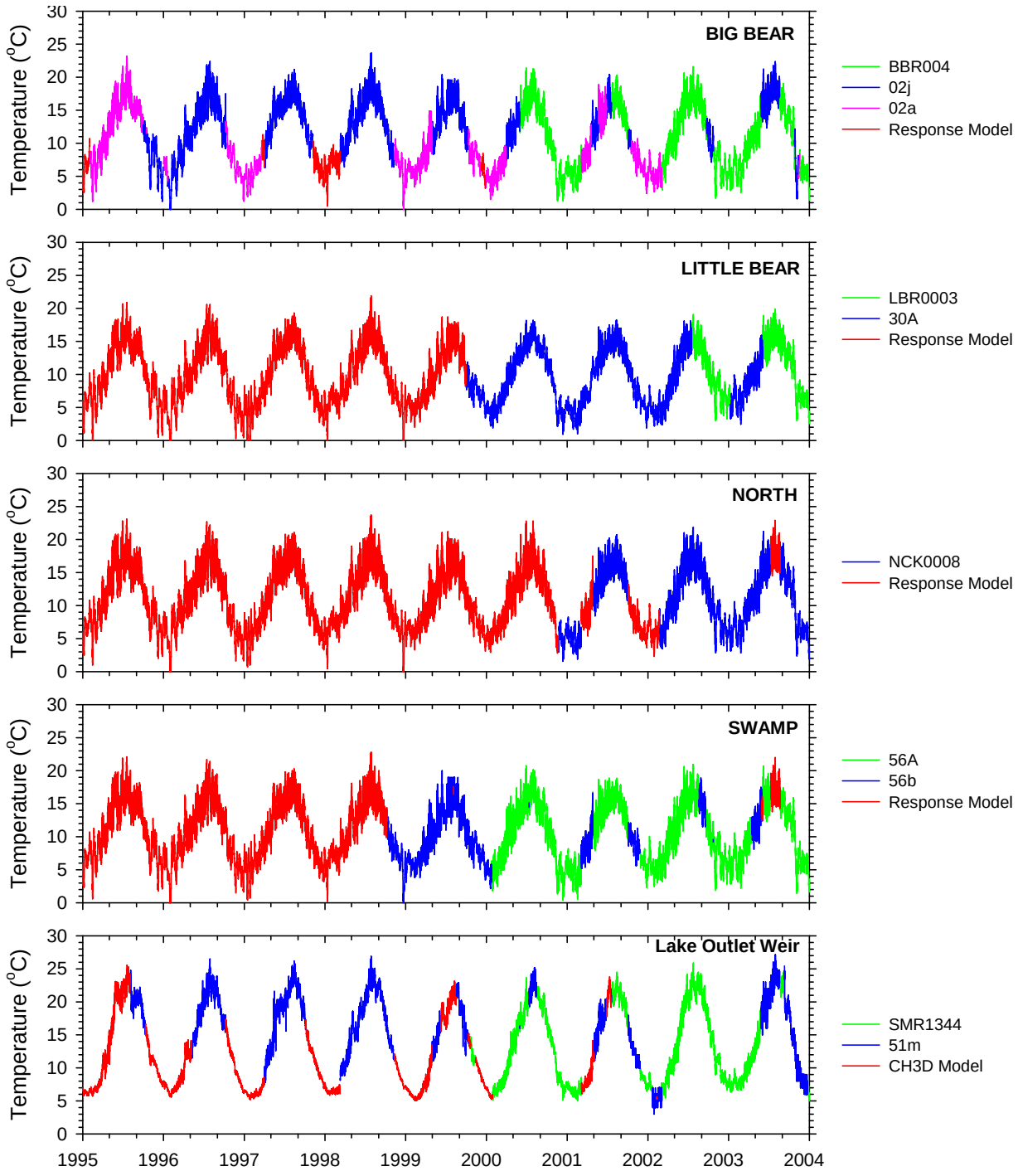


Figure 19 Model temperature boundary conditions developed from continuous temperature records and a response temperature model.

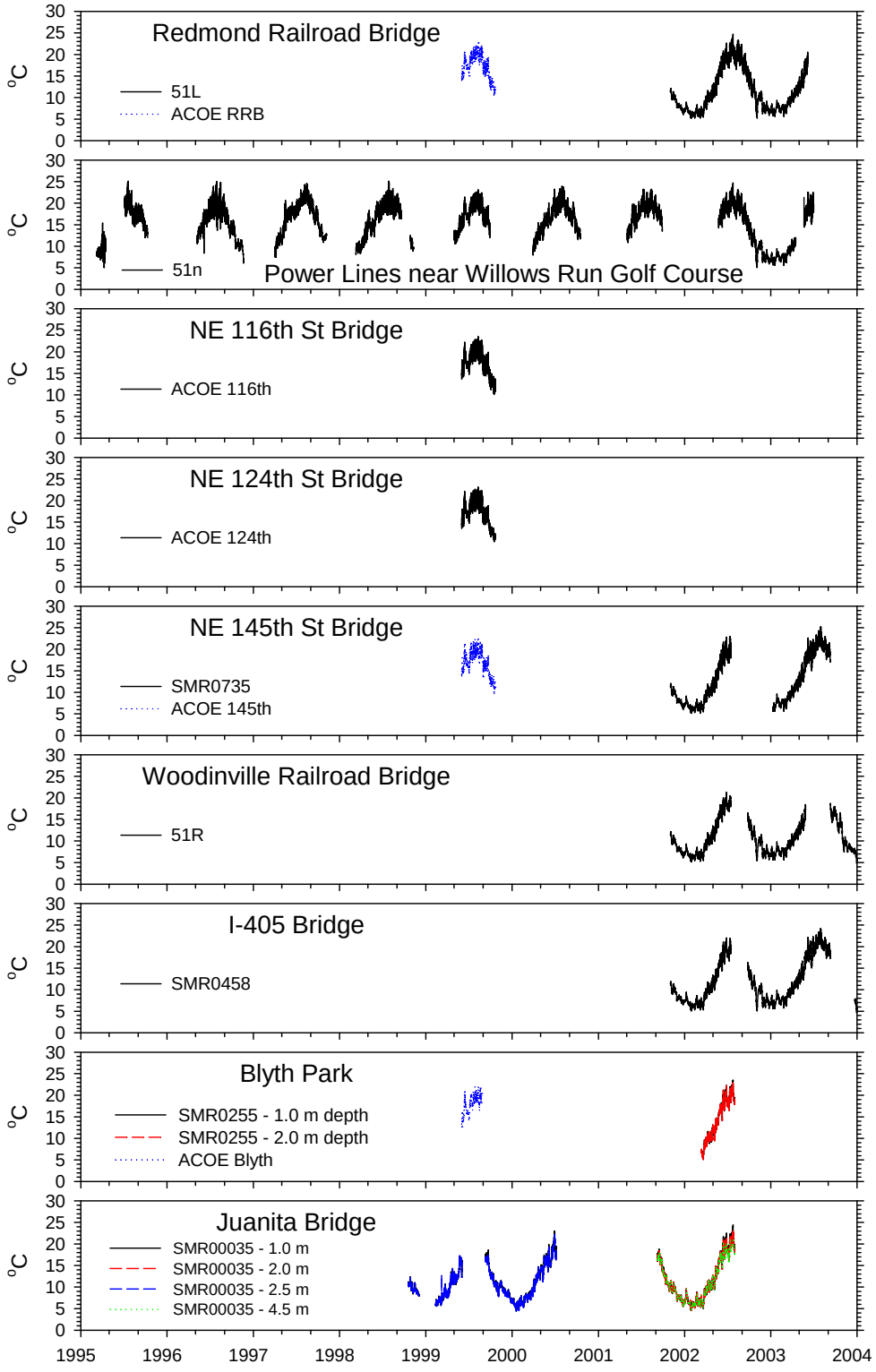


Figure 20 Continuous temperature data used in model calibration.

available calibration data generally correspond with periods of temperature observations for the upstream boundary and tributaries.

Forward-Looking Infrared (FLIR) images of the Sammamish River taken in September 2, 1999 and March 23, 2000 (Watershed Sciences 2000a and 2000b) provide an additional data set for evaluation of model temperature predictions. FLIR provides a snapshot in time of river surface temperatures. Evaluation of the model developed by JEEAI for the Seattle District ACOE with respect to the September 1999 FLIR data initiated some changes to the model configuration to better reproduce the elevated temperatures observed in the lower river below Bothell (King County 2002 – Appendix B). The FLIR surface temperature profiles used in the model calibration described in this report are shown in Figure 21.

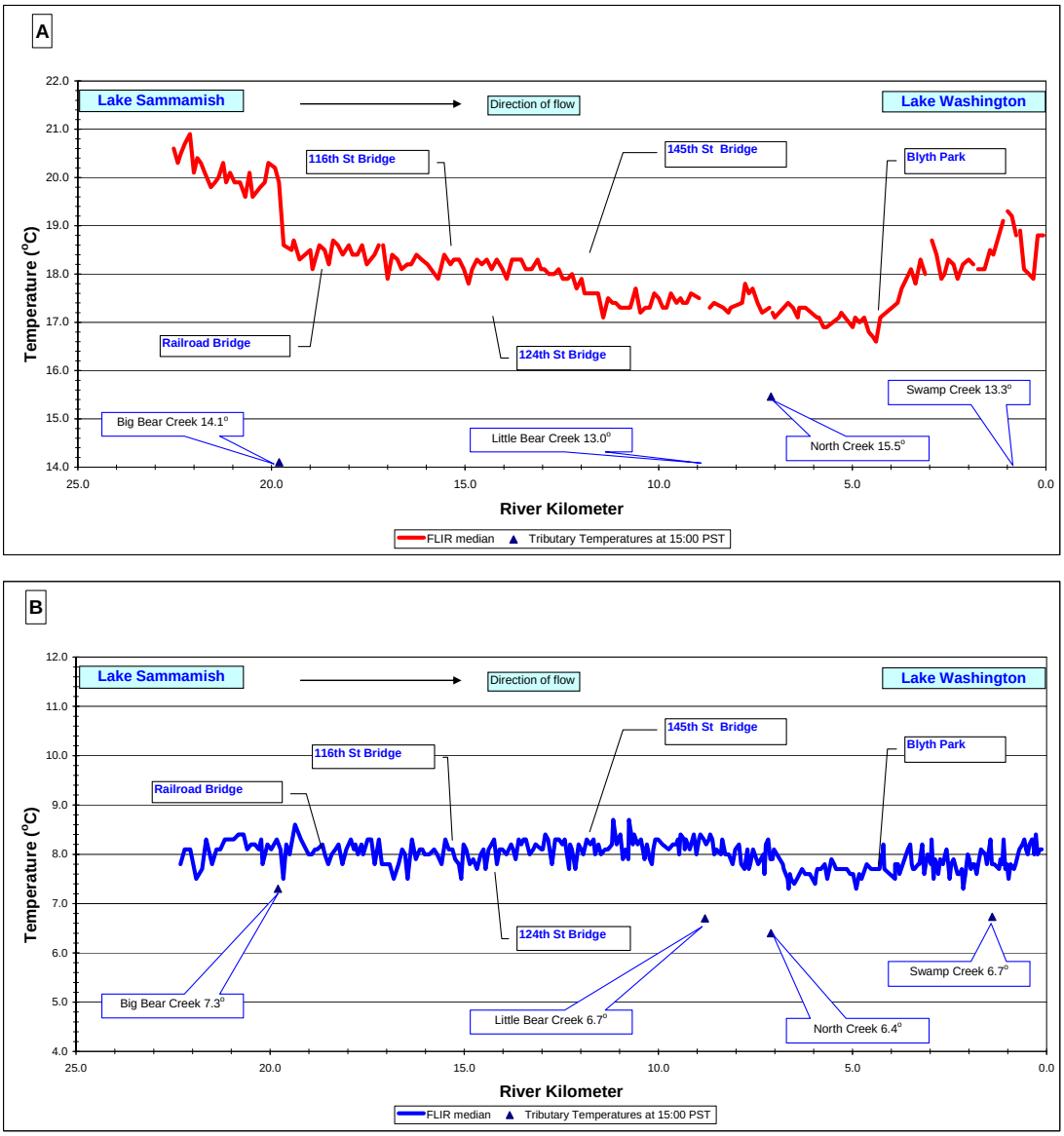


Figure 21. Forward-looking Infrared (FLIR) profiles. (A) September 2, 1999 approximately 2:00 PM PST. (B) March 23, 2000 approximately 8:45 AM PST. Note change in scale between figures.

4.3.1.4 Downstream Boundary

Downstream temperature boundary conditions for 1995-2003 were developed using the routine (monthly to twice monthly in summer) temperature monitoring data collected by King County at Lake Washington station 0804 nearest the Sammamish River outlet (Table 4, Figure 22).

Temperature profiles available for the modeling period were interpolated onto the downstream model grid. A color contour plot of the available downstream temperature boundary condition temperature data are provided in Figure 22.

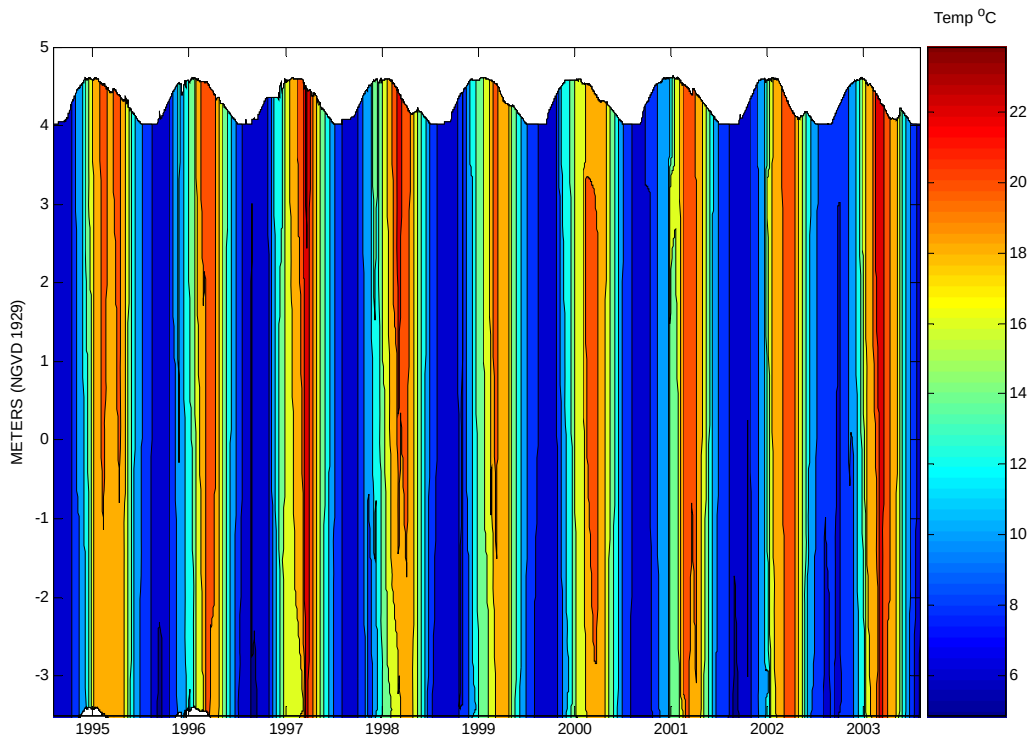


Figure 22 Model temperature downstream boundary condition developed from routine monitoring at Station 0804 at the north end of Lake Washington.

4.3.2 Water Quality Constituents

Apart from temperature data described above, water quality constituents used in the development of the model include dissolved oxygen (DO), pH, specific conductance, total suspended solids (TSS), total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), nitrate plus nitrite nitrogen (NO3-N), total ammonia nitrogen (TNH3-N), dissolved silica, total organic carbon (TOC), dissolved organic carbon (DOC), chlorophyll *a*, total and dissolved copper and the indicator bacteria fecal coliform and *Escherichia coli*. These data have been collected at a number of locations for varying lengths of time (Table 4, Figure 17). Ideally, the frequency of water quality observations would match the temporal variability of the particular constituent of interest. Although this is feasible for temperature data, resource limitations and limited monitoring scope have precluded the collection of most water quality data to anything more

frequent than monthly[9]. This may be adequate for many water quality parameters. However, constituents whose temporal variability is strongly influenced by rainfall wash off events from relatively small drainage basins (in this case 2nd and 3rd order streams similar to the 4 major Sammamish River tributaries that are currently monitored) will likely be poorly represented by routine sampling. Furthermore, routine sampling designed to detect long-term trends is not necessarily adequate for developing continuous (in this case hourly) water quality boundary conditions for use in a dynamic long-term simulation model.

In addition to issues associated with temporal variability, one should recognize that the water quality model's state variables are not necessarily interchangeable with the observed water quality constituents. The best examples of this are the state variables that track labile and refractory organic matter in the model, which are functional representations – but not equivalent to – TOC/DOC. The required model constituents and steps chosen to transform observed parameters to model constituents are specified below.

A special continuous study of diel DO, pH, specific conductance and temperature was conducted during summer of 2003 (King County 2005b), which indicates that in addition to temperature, DO and pH also exhibit relatively large diel variations (especially in the river reach between the upstream boundary and the confluence with Little Bear Creek) that would best be characterized by high frequency data collection. The suspected cause of the diel fluctuation is the dense growth of submerged aquatic plants observed in the river during summer (King County 2005b). These data provide a limited data set for testing the ability of the model to simulate the effect of macrophyte growth on DO and pH fluctuations in the river in 2003.

The available data and methods used to develop hourly water quality model boundary condition inputs and available calibration data are described below. Also, as recommended by the King County Environmental Laboratory (King County 1996), chlorophyll *a* concentrations analyzed after June 1996 using a different methodology were multiplied by 1.14 to provide data comparable to data generated by the previous method. A similar bias has been noted in TP data reported after a methodology change in July 1998. A preliminary correction was applied to TP values reported beginning in July 1998 – TP (mg/L) x 1.2 + 0.002.

4.3.2.1 Upstream Boundary

The upstream water quality boundary condition was specified as daily constituent concentrations using routine monitoring data from the Marymoor Park station 0486 (located just below the lake outlet weir) for all constituents and from Lake Sammamish station 0625 near the lake outlet (Table 4, Figure 17). Routine water quality monitoring has been conducted since December 1971 at 0486 and at 0625 since February 1995, which provides relatively continuous records for the development of the model upstream constituent boundary condition for the 1995-2003 simulation period. Exceptions include the lack of chlorophyll *a* (only at 0486), dissolved silica, and TOC/DOC data until April 2002 (Figure 23 and Figure 24). Long-term chlorophyll *a* data

[9] King County's routine stream monitoring program has also included wet and dry-weather season storm sampling (up to 6 additional grab samples per season) as early as 1993 at some locations.

for 0625, which were very similar to the available 0486 data (Figure 25), provided the necessary chlorophyll *a* data for specification of the upstream algal biomass inputs. Relatively limited data were available for copper at 0486 and 0625 (Figure 26); therefore an average outlet total copper concentration based on the available data was specified at the upstream boundary (0.7 µg/L).

For 2003, the available hourly continuous DO, pH and specific conductance data collected as part of a special study (King County 2005b) was incorporated into the upstream boundary constituent input file by linearly interpolating the remaining constituent inputs derived from the routine data to an hourly frequency (Figure 27).

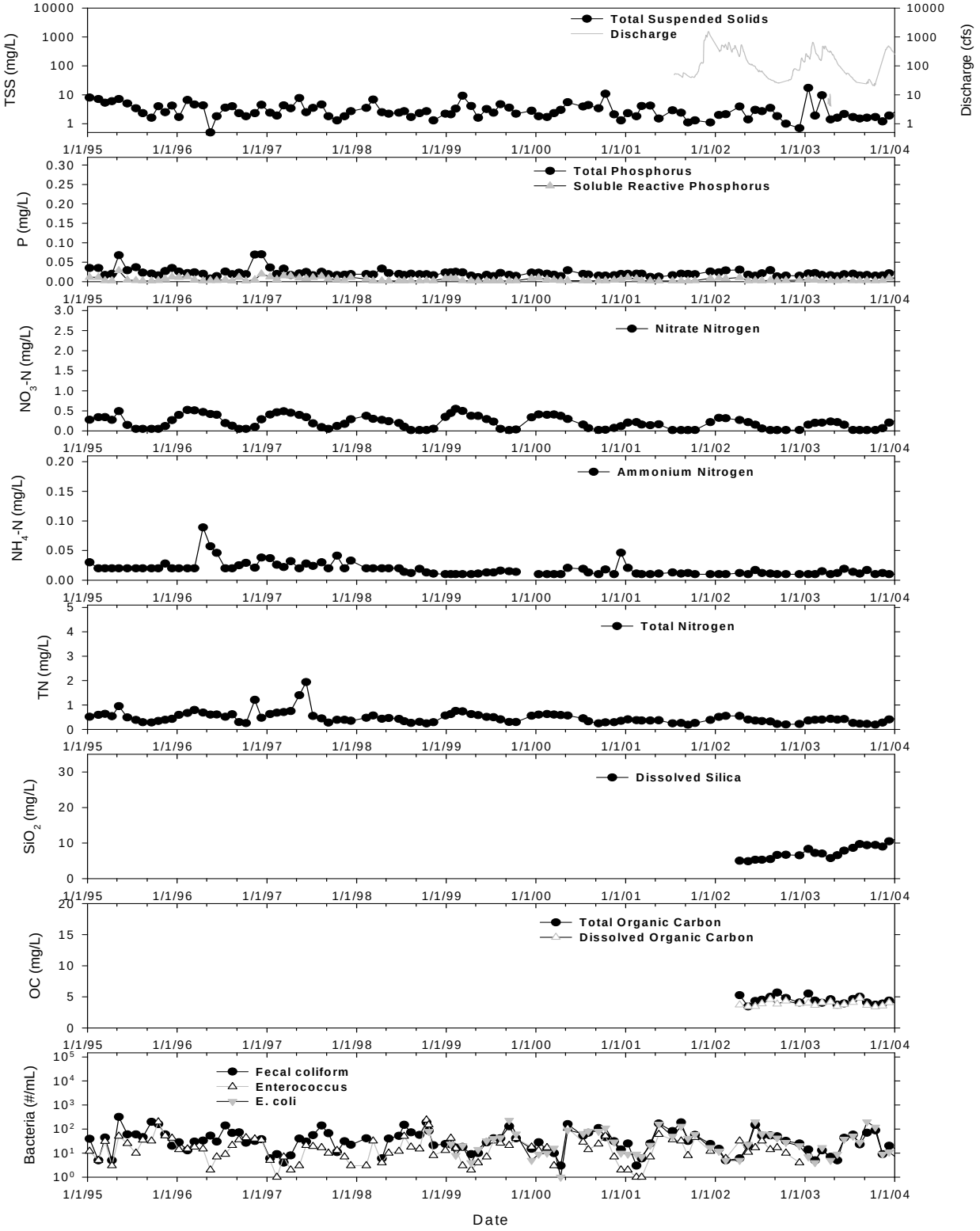


Figure 23 Water quality data for Sammamish River at Marymoor Park (0486), 1995-2003. All discharge data from Sammamish weir gauge 51m upstream of 0486.

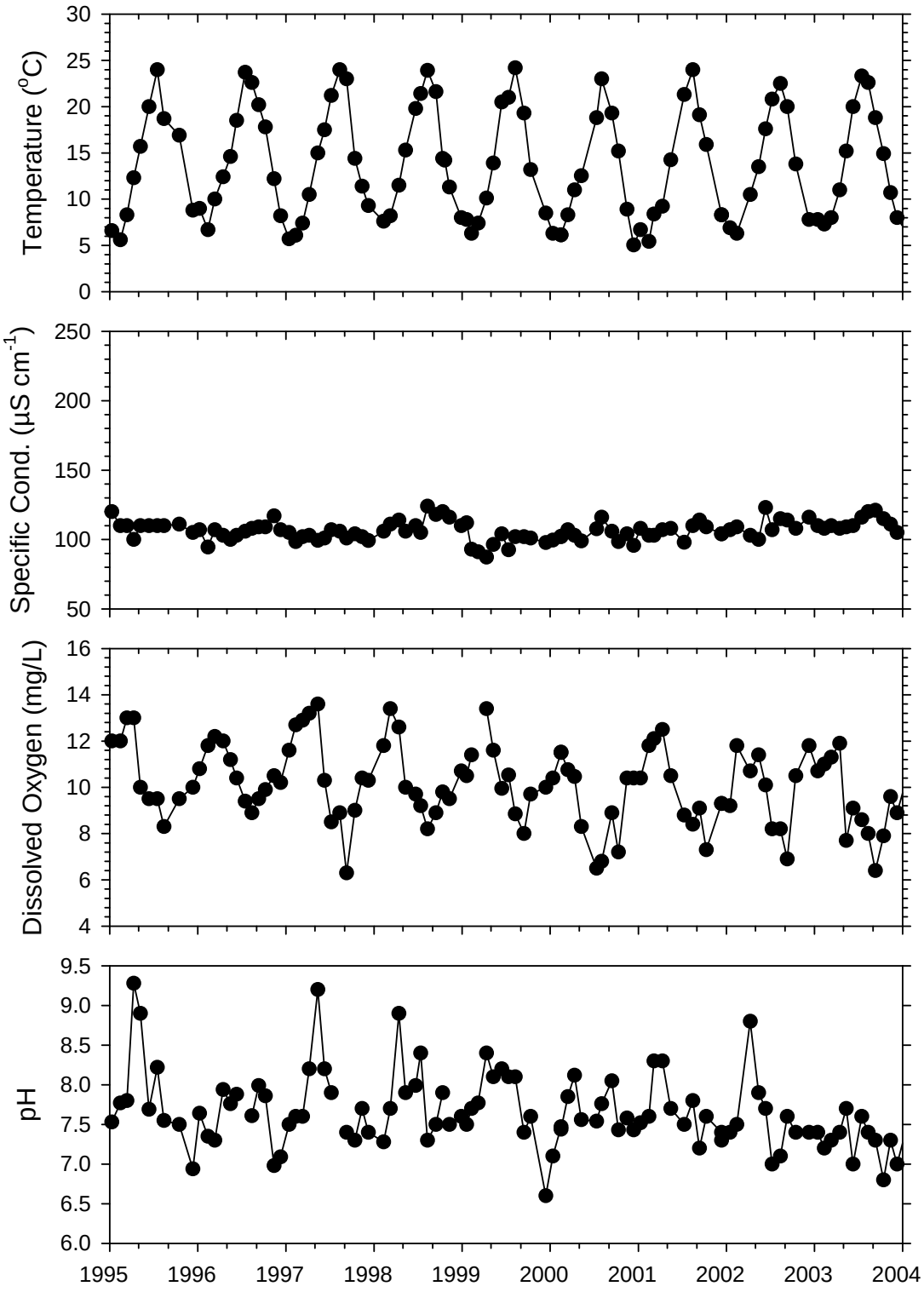


Figure 24 Temperature, conductance, DO and pH data for Sammamish River at Marymoor Park (0486), 1995-2003.

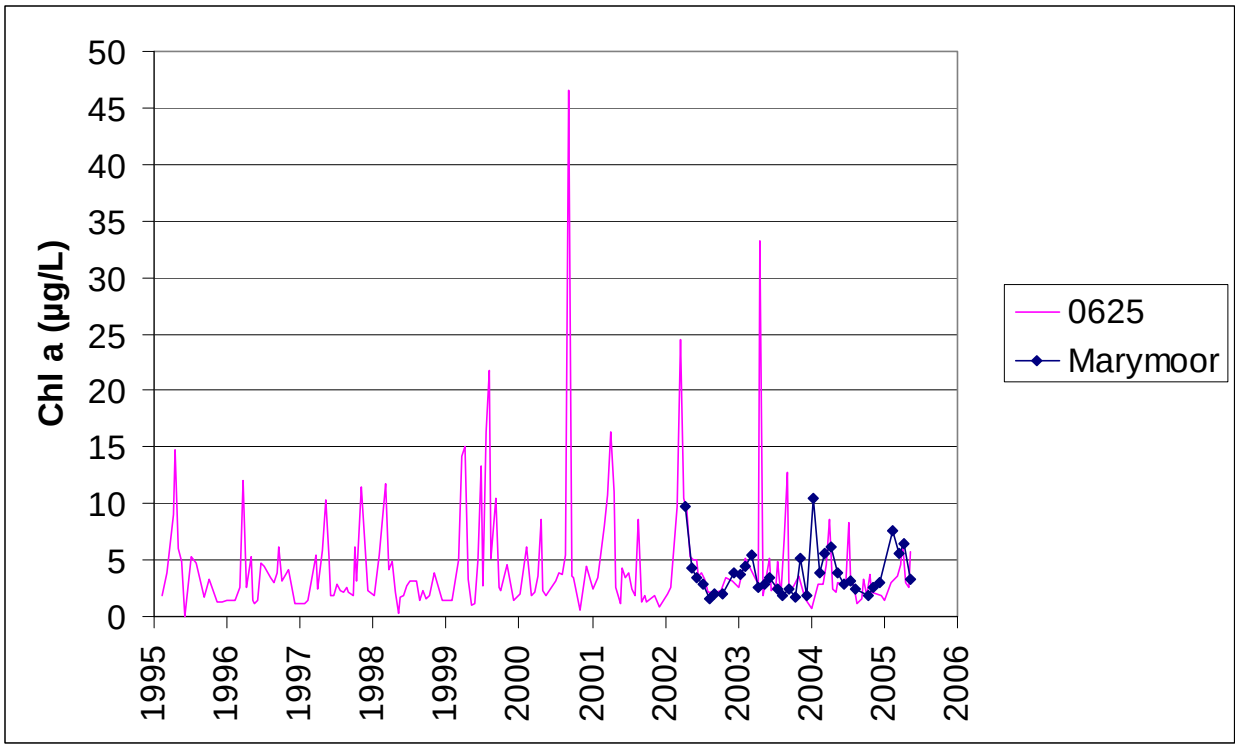


Figure 25 Chlorophyll *a* data at Lake Sammamish 0625 and Marymoor Park 0486, 1995-2005.

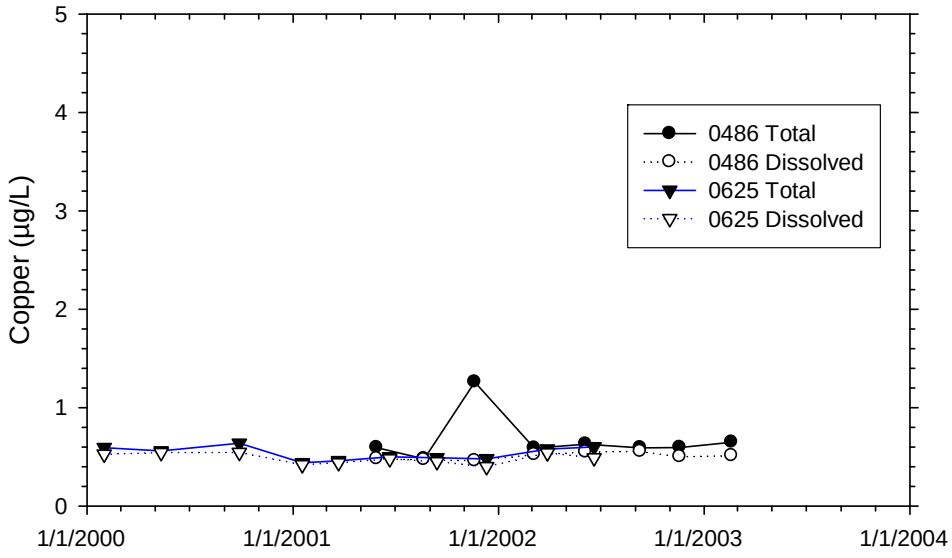


Figure 26 Total and dissolved copper data at Lake Sammamish 0625 and Marymoor Park 0486, 1995-2005.

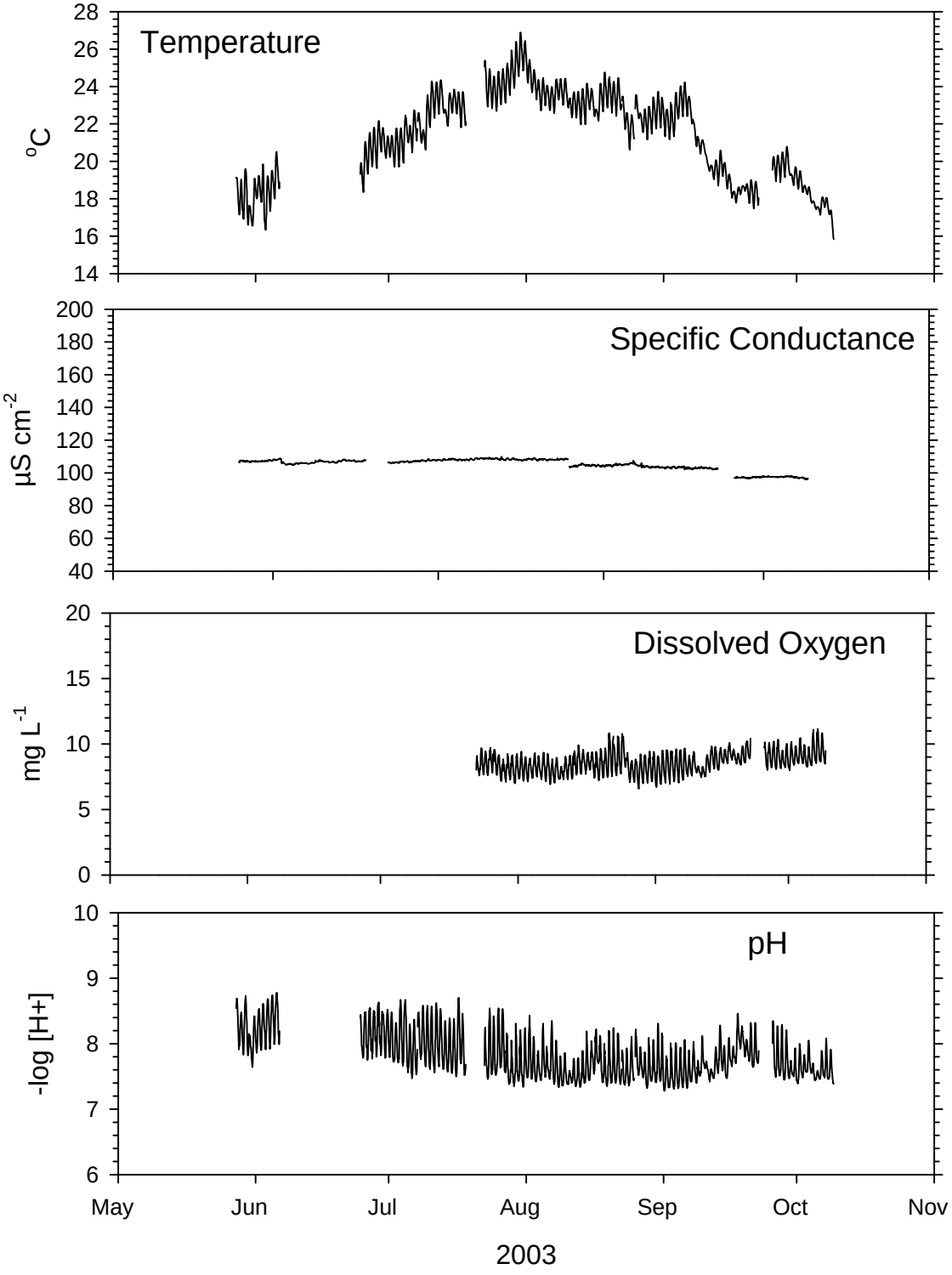


Figure 27 Continuous (hourly) sonde data collected at the Redmond Rowing Club during the summer, 2003 (see King County 2005b for details).

After the available data were assembled, linear interpolation and additional processing and transformation steps were necessary to provide appropriate constituent inputs to the model. Linear interpolation of observations was considered to be a suitable approach given the limited temporal variation in observations (see Figure 23 through Figure 27), with the possible exception of temperature, DO and pH.

The diel variation in temperature, particularly during summer was addressed using more frequent (hourly) observations and dynamic model simulations (see above). An investigation of diel variation of DO and pH conducted in the summer of 2003 (King County 2005) allowed for the evaluation of the importance of capturing the higher-frequency variation of upstream boundary DO and pH. The required model constituents and transformation steps are documented in Table 6 and Figure 28.

4.3.2.2 Tributaries

Major tributary water quality boundary conditions were specified as hourly constituent concentrations using routine monitoring data from the monitoring locations nearest the mouth of each creek (Table 4, Figure 17). Routine water quality monitoring has been conducted since December 1971 at these stations, which provides relatively continuous records for the development of the model tributary constituent boundary condition for the 1995-2003 simulation period (Figure 29 through Figure 36). Exceptions include the lack of dissolved silica and TOC/DOC data until March 2002, chlorophyll *a* data until April 2002 (Figure 37), and copper since early 1998 (Figure 38). From the available data for all four tributaries a typical chlorophyll *a* time series was developed to create an input time series for the pre-April 2002 period (see Figure 37).

Available TOC (and DOC) data were limited to March 2002 and later (Figure 39). As in the development of the Lake Sammamish water quality model (King County 2008), these data were used to develop regression equations to predict TOC from the amount of organic nitrogen in the water [TN – (NO3-N + TNH3-N)]. Tributary TOC data were needed to needed to develop the labile and refractory organic matter (dissolved and particulate) inputs to the model. Specific regression equations were developed for each tributary (Figure 40).

After the available data were assembled, linear interpolation and additional processing and transformation steps, in addition to those already described above, were necessary to provide appropriate constituent inputs to the model. Linear interpolation of observations was considered to be a suitable approach given the limited temporal variation in most observations; especially dissolved nutrients (see Figure 29 through Figure 36). Exceptions include TSS, TP, fecal coliform, *E. coli* and total copper due to their association with particulate matter wash-off during rain storms. Other exceptions include summer temperature, DO, and pH. The diel variation in temperature, particularly during summer was addressed using more frequent (hourly) observations and dynamic model simulations (see above).

For 2003, the available hourly continuous DO, pH and specific conductance data collected in Big Bear Creek as part of a special study (King County 2005b) was incorporated into Big Bear Creek constituent input file (Figure 41).

Table 6. CE-QUAL-W2 state variables and transformations used to convert observations to model upstream boundary condition inputs.

W2 State Variable	Observation data transformation
Temperature, ^{o}C	Temperature, ^{o}C (no transformation)
Total Dissolved Solids, mg/L (TDS)	Specific Conductance, µS/cm x 0.55 (Hem 1992)
Conservative Tracer, mg/L (TRACER)	Arbitrary/User defined as needed
Total Copper, mg/L (TCu)	Total copper, µg/L x ucf
Fecal Coliform, no./100 mL (FC)	Fecal coliform, no./100 mL (no transformation)
E.coli, no./100 mL (EC)	*E. coli*, no./100mL (no transformation)
Inorganic Suspended Solids (iSS)	Total Suspended Solids, mg/L (TSS) – Particulate Organic Matter (POM), where POM = [OM:C x Total Organic Carbon (TOC) x (1 – fdoc)]
Bioavailable Phosphorus, mg/L (PO4)	Soluble Reactive P, mg/L (no transformation)
Ammonia Nitrogen, mg/L (NH4)	Ammonia Nitrogen, mg/L (no transformation)
Nitrate Nitrogen, mg/L (NO3)	Nitrate Nitrogen, mg/L (no transformation)
Dissolved Silica, mg/L (dSi)	Dissolved Silica, mg/L (SiO_2) x 0.47 (convert from SiO_2 to Si)
Particulate Biogenic Silica, mg/L (PSi)	DIA x 1/(OM:C) x (Si:C) (covert diatom biomass to PSi)
Labile Dissolved Organic Matter, mg/L (LDOM)	2.2 x TOC x fdoc x flabile
Refractory Dissolved Organic Matter, mg/L (RDOM)	2.2 x TOC x fdoc x (1 - flabile)
Labile Particulate Organic Matter, mg/L (LPOM)	2.2 x TOC x (1 – fdoc) x flabile
Refractory Particulate Organic Matter, mg/L (RPOM)	2.2 x TOC x (1 – fdoc) x (1 – flabile)
Blue Green Algae, mg dw/L (BGR)	Chl *a*, µg/L ÷ ucf x fBGR x (C:Chla) x OM:C
Diatom Algae, mg dw/L (DIA)	Chl *a*, µg/L ÷ ucf x fDIA x (C:Chla) x OM:C
Green Algae, mg dw/L (GRN)	Chl *a*, µg/L ÷ ucf x fGRN x (C:Chla) x OM:C
Dissolved Oxygen, mg/L (DO)	Dissolved Oxygen, mg/L (no transformation)
Total Inorganic Carbon, mg/L (TIC)	*f*(temperature, pH, alkalinity)
Alkalinity, mg $CaCo_3$/L	Total Alkalinity, mg/L (no transformation)
Ucf (unit conversion factor, µg/L to mg/L) = 1000; OM:C (dry weight Organic Matter to Carbon ratio) = 2.2; fdoc (fraction DOC) = 0.9; Si:C (silica to carbon ratio) = 0.6; flabile (fraction labile Organic Matter) = 0.3; fBGR (fraction of chlorophyll as Blue Green Algae) = 0.2; fDIA (fraction of chlorophyll as Diatom) = 0.5; fGRN (fraction of chlorophyll as Green Algae) = 0.3; C:Chla (carbon to chlorophyll a ratio) = 50	

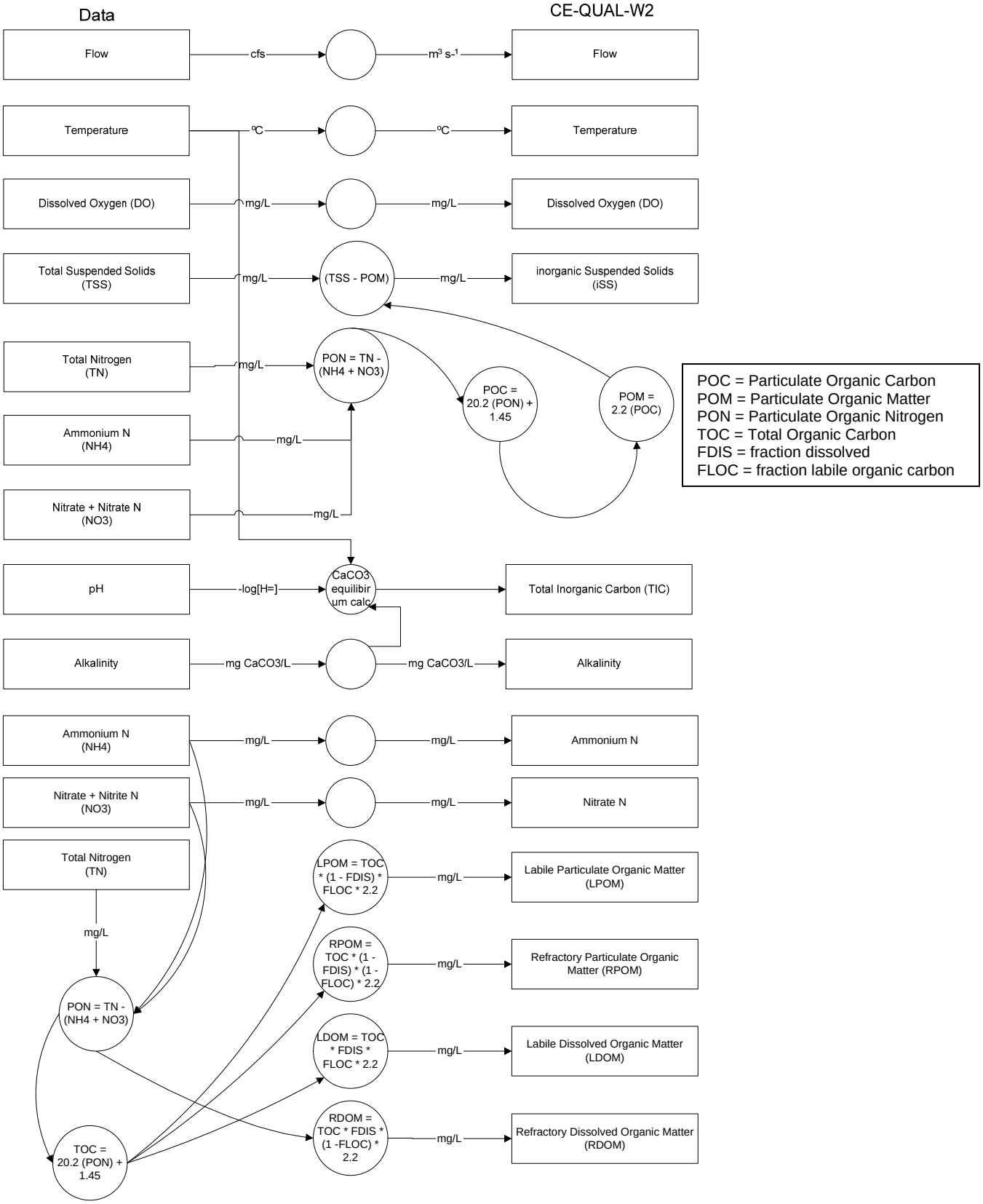


Figure 28 Linkage of CE-QUAL-W2 to monitoring data.

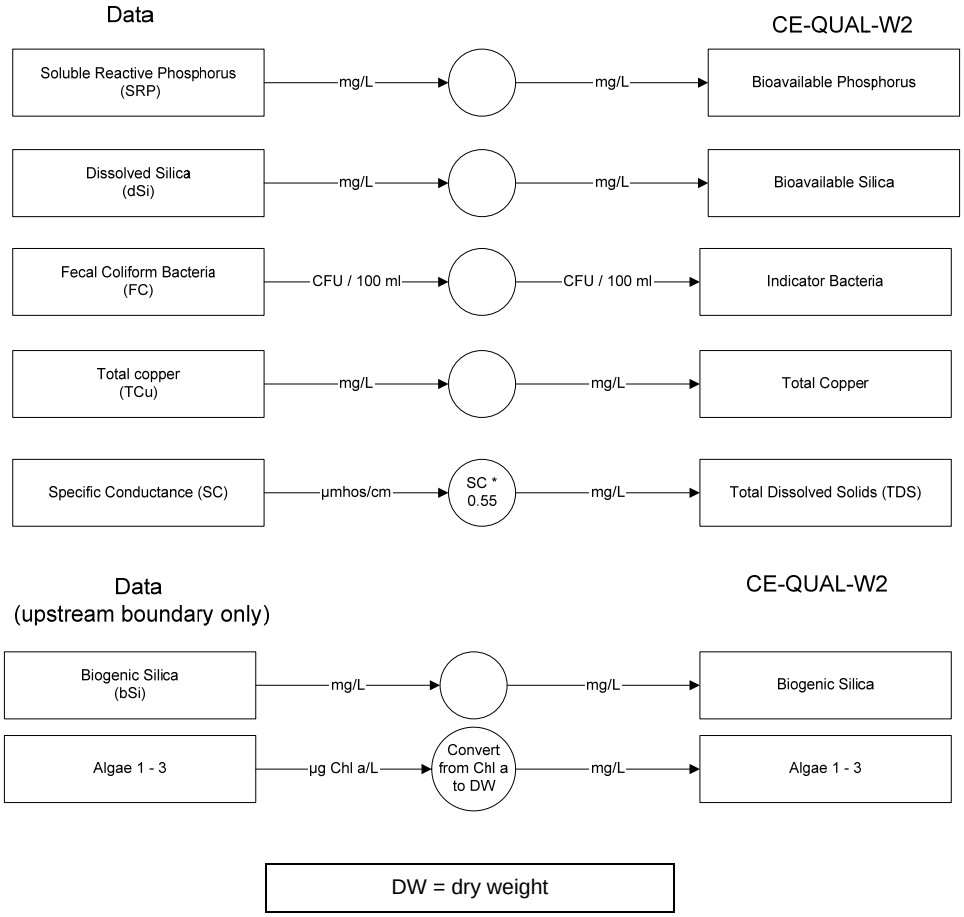


Figure 28 Linkage of CE-QUAL-W2 to monitoring data (continued).

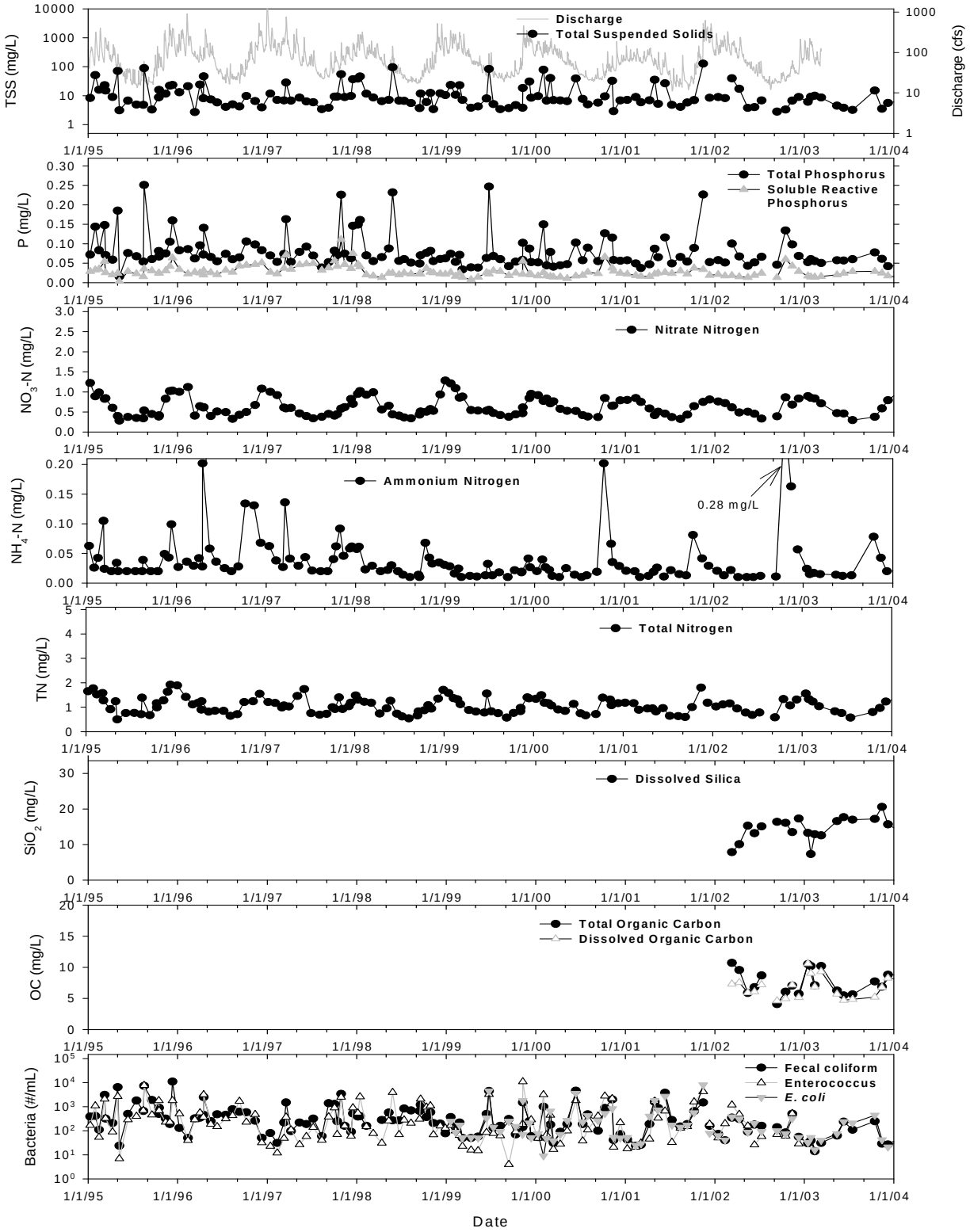


Figure 29 Water quality data for Big Bear Creek (0484), 1995-2003. All discharge data from Bear Creek gauge 02a.

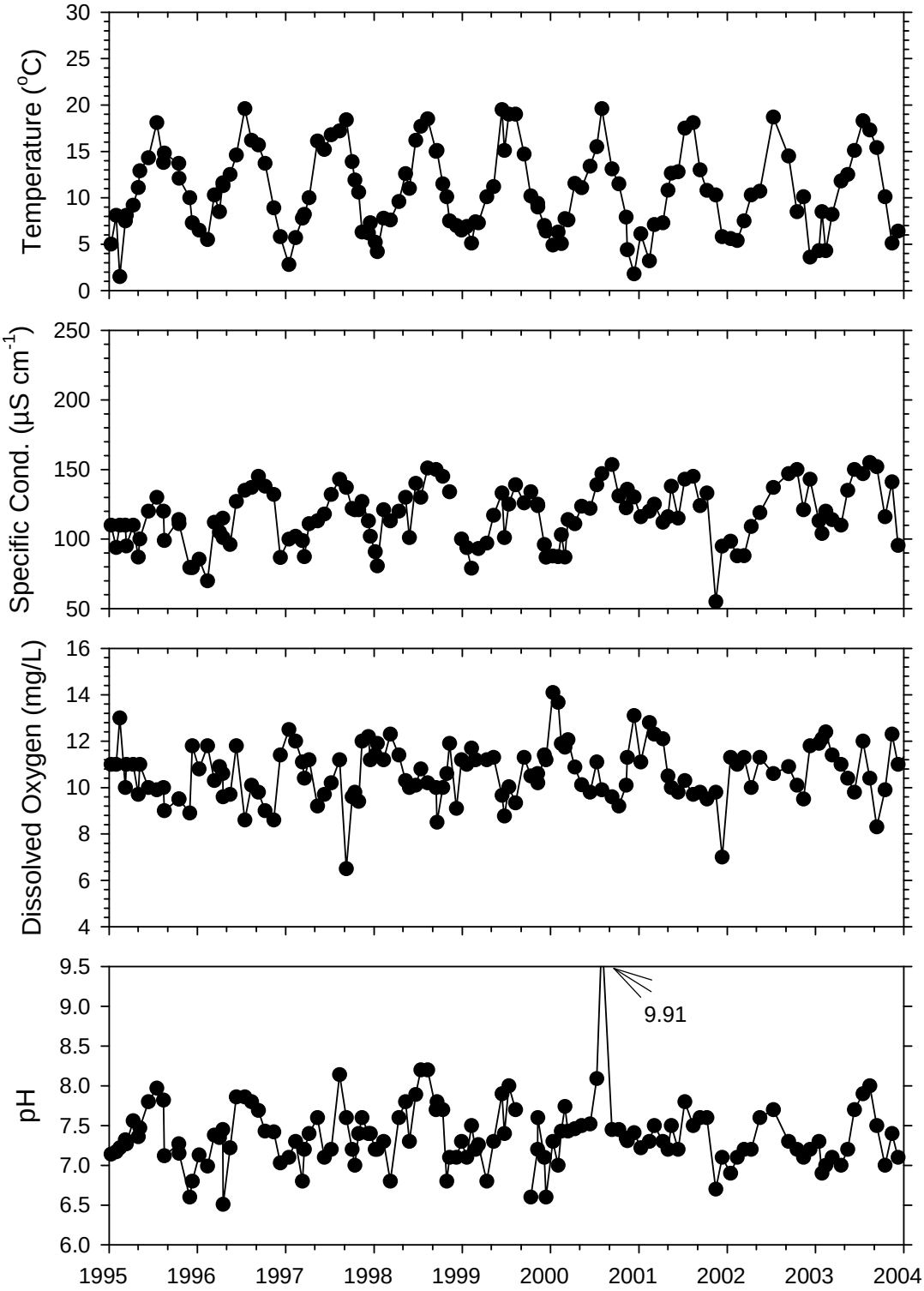


Figure 30 Temperature, conductance, DO and pH data for Big Bear Creek (0484), 1995-2003.

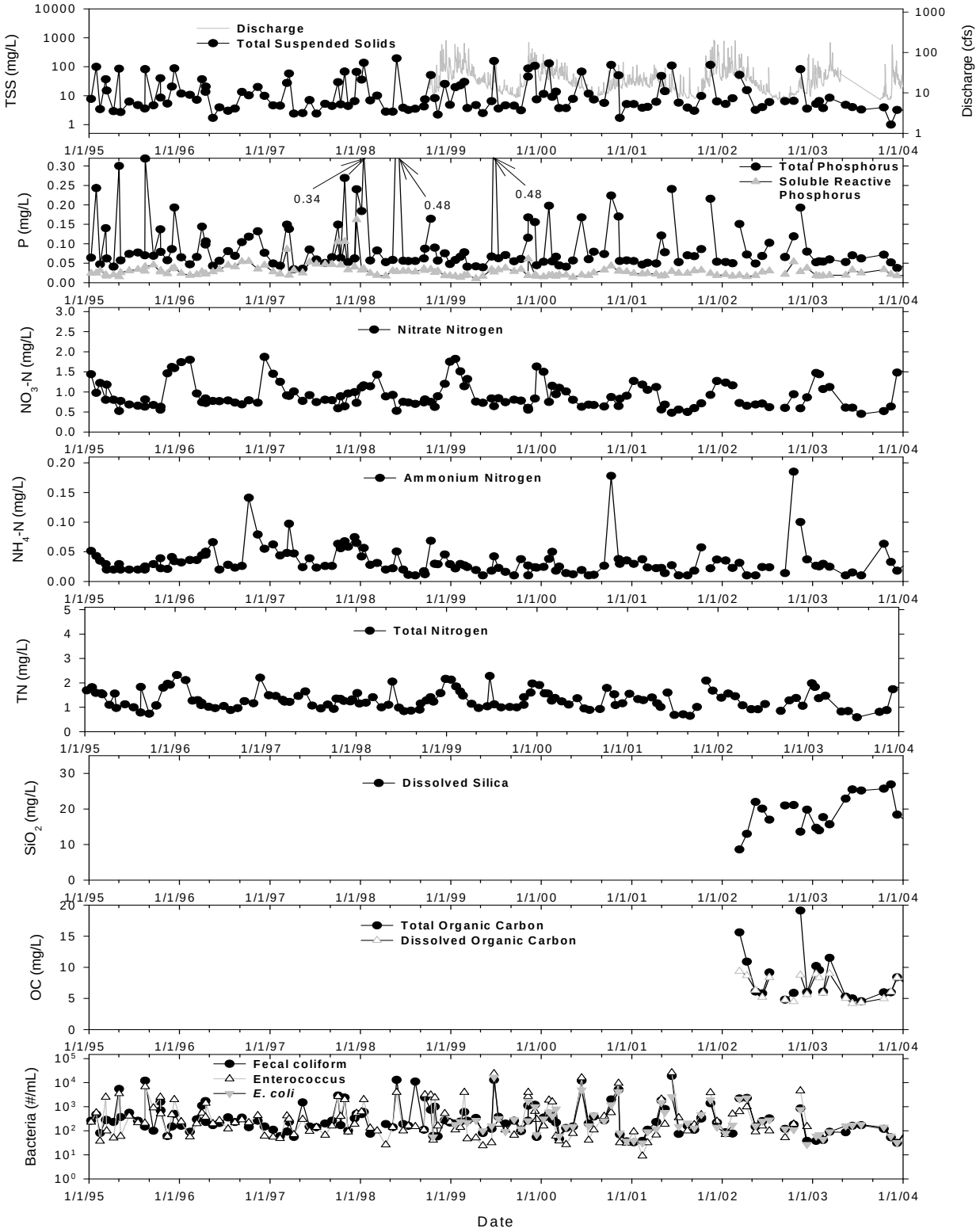


Figure 31 Water quality data for Little Bear Creek (0478), 1995-2003. All discharge data from Bear Creek gauge 30a.

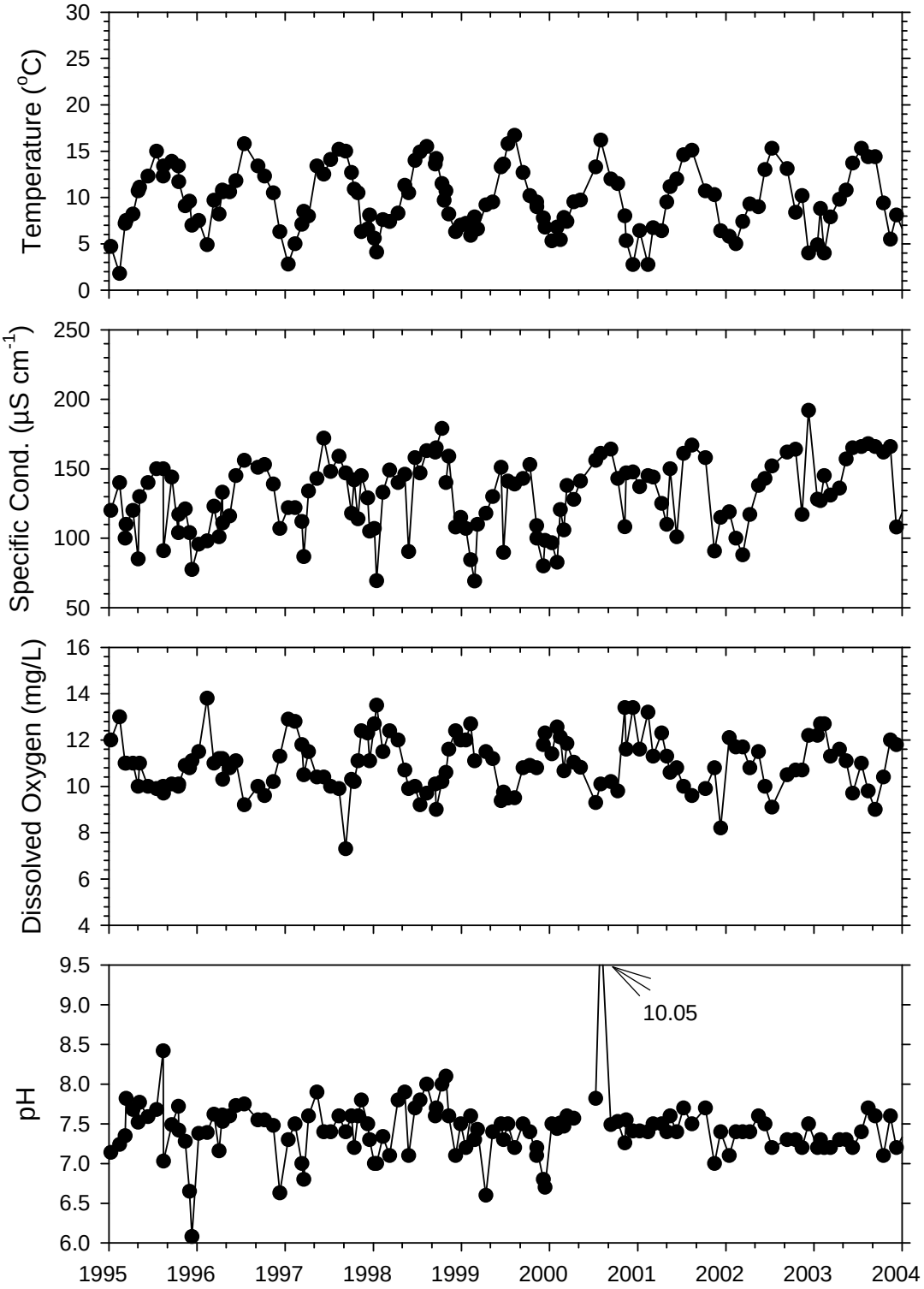


Figure 32 Temperature, conductance, DO and pH data for Little Bear Creek (0478), 1995-2003.

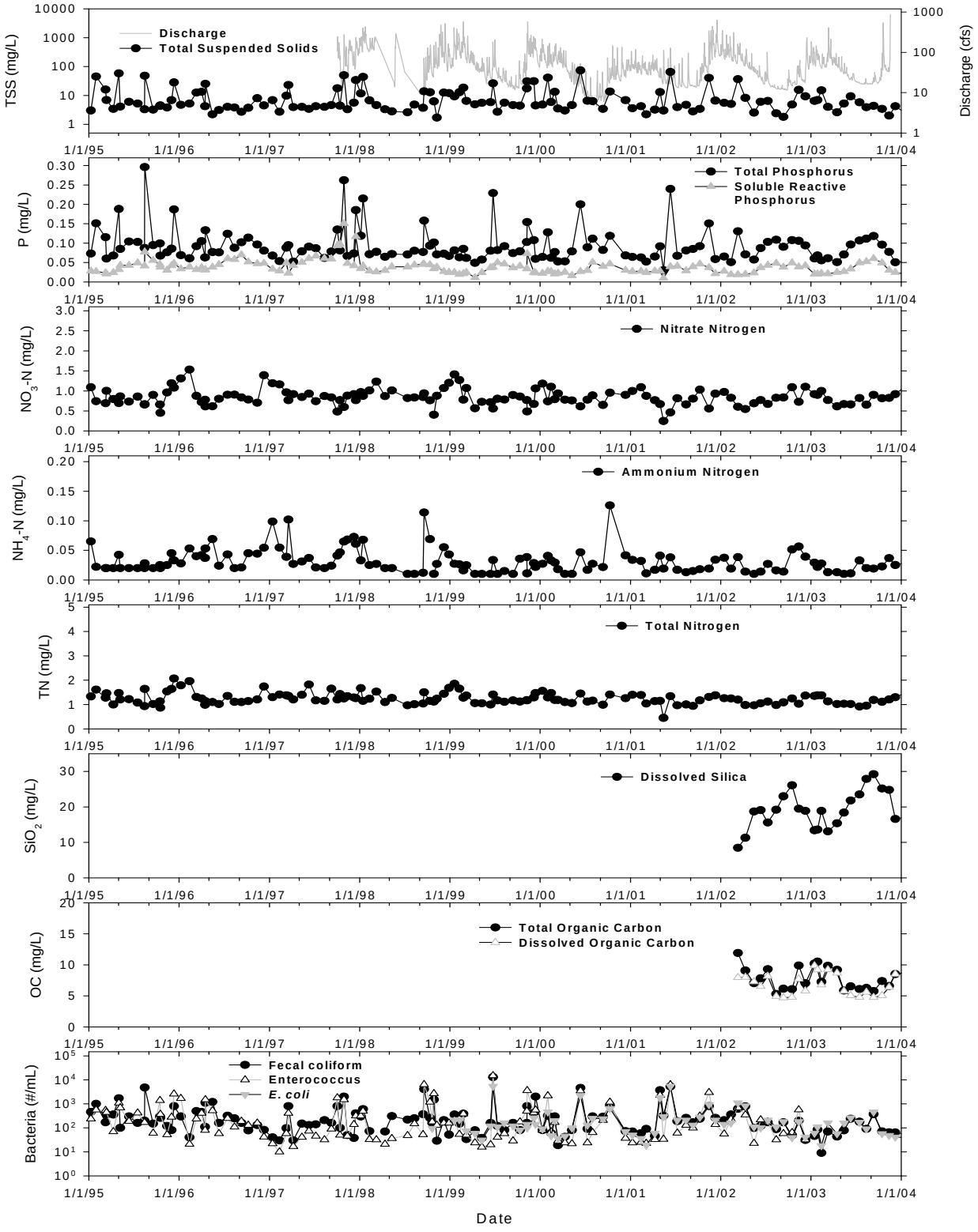


Figure 33 Water quality data for North Creek (0474), 1995-2003. All discharge data from Snohomish County gauge at county line (45Nc).

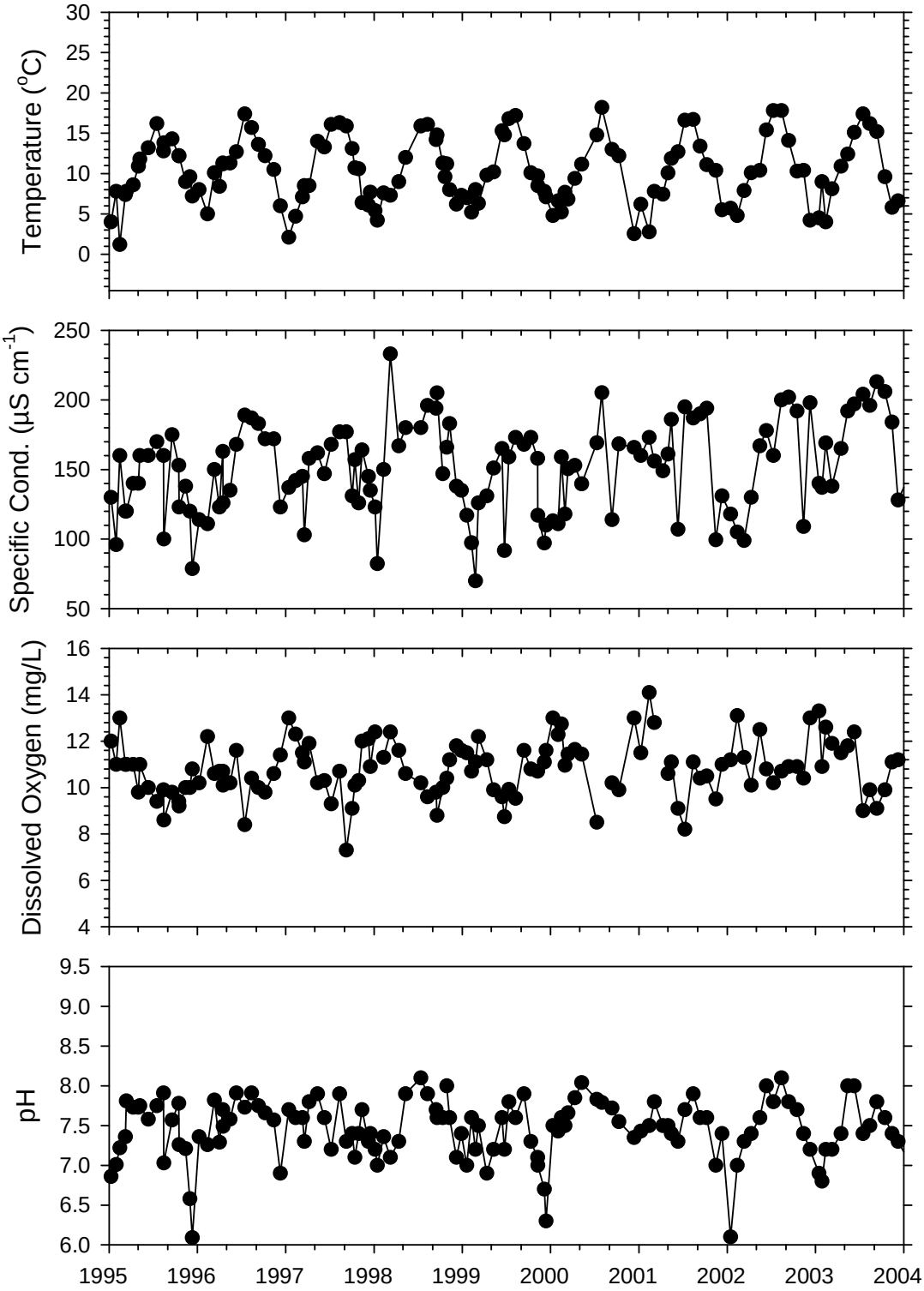


Figure 34 Temperature, conductance, DO and pH data for North Creek (0474), 1995-2003.

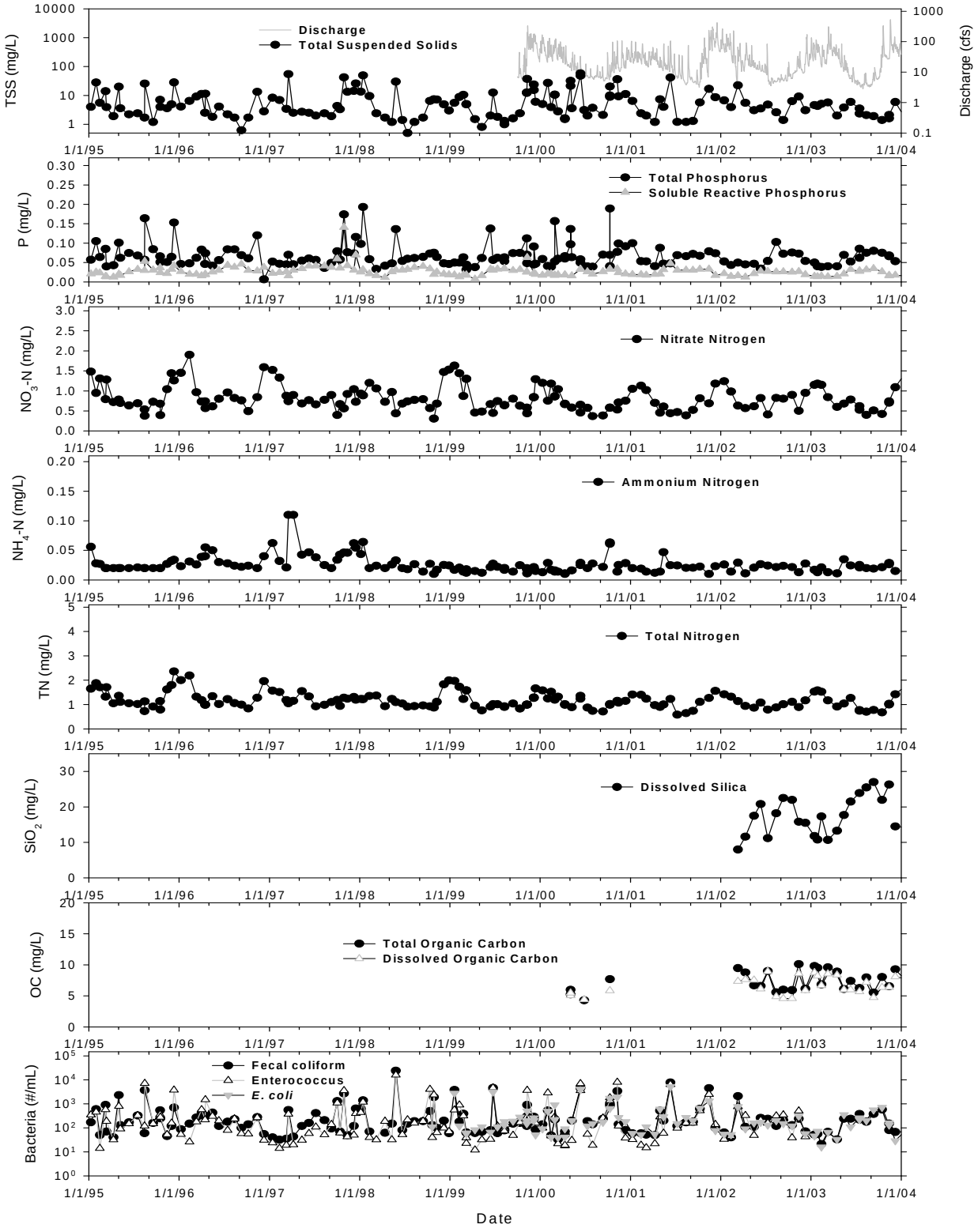


Figure 35 Water quality data for Swamp Creek (0470), 1995-2003. All discharge data from King County gauge (56b).

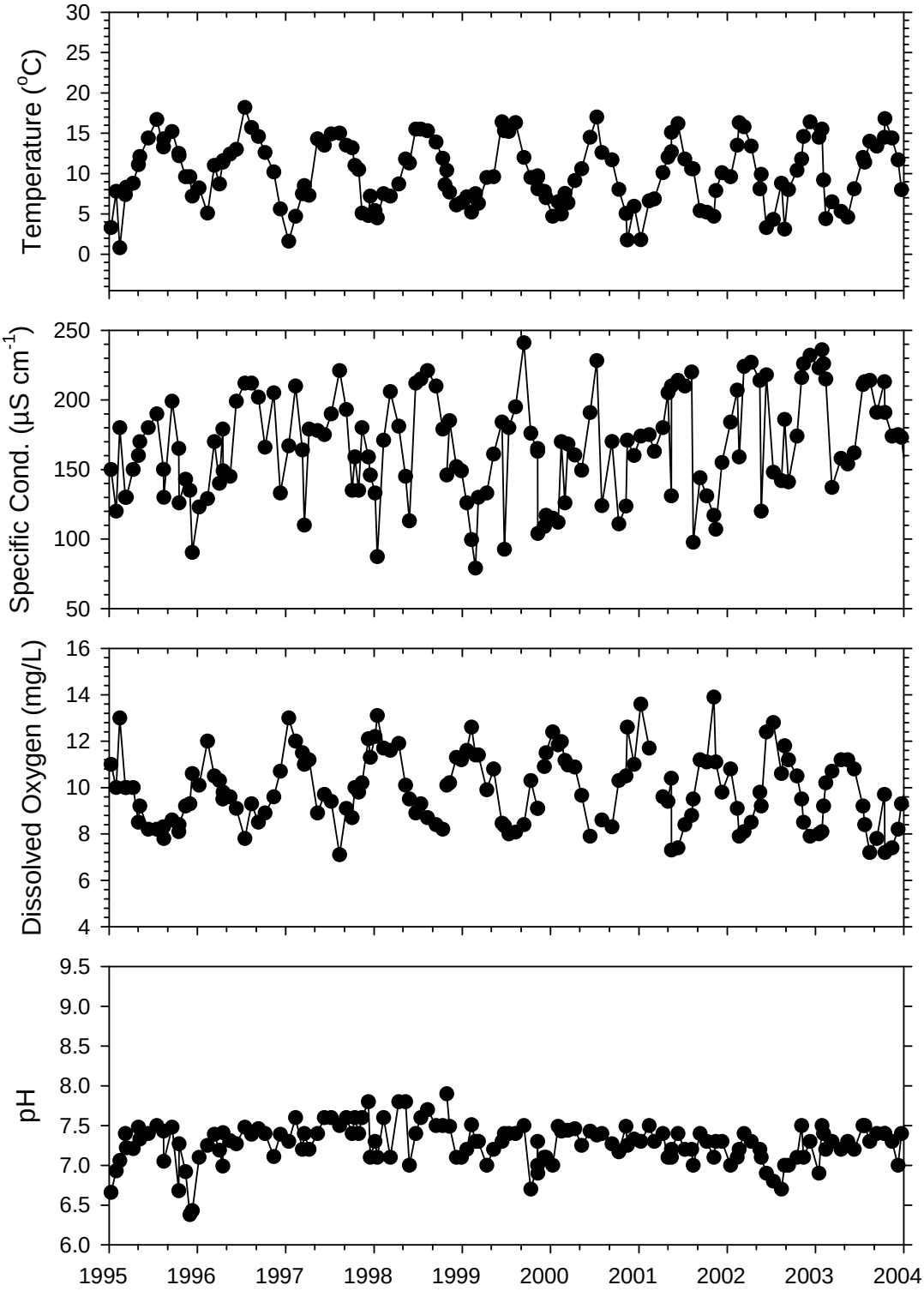


Figure 36 Temperature, conductance, DO and pH data for Swamp Creek (0470), 1995-2003.

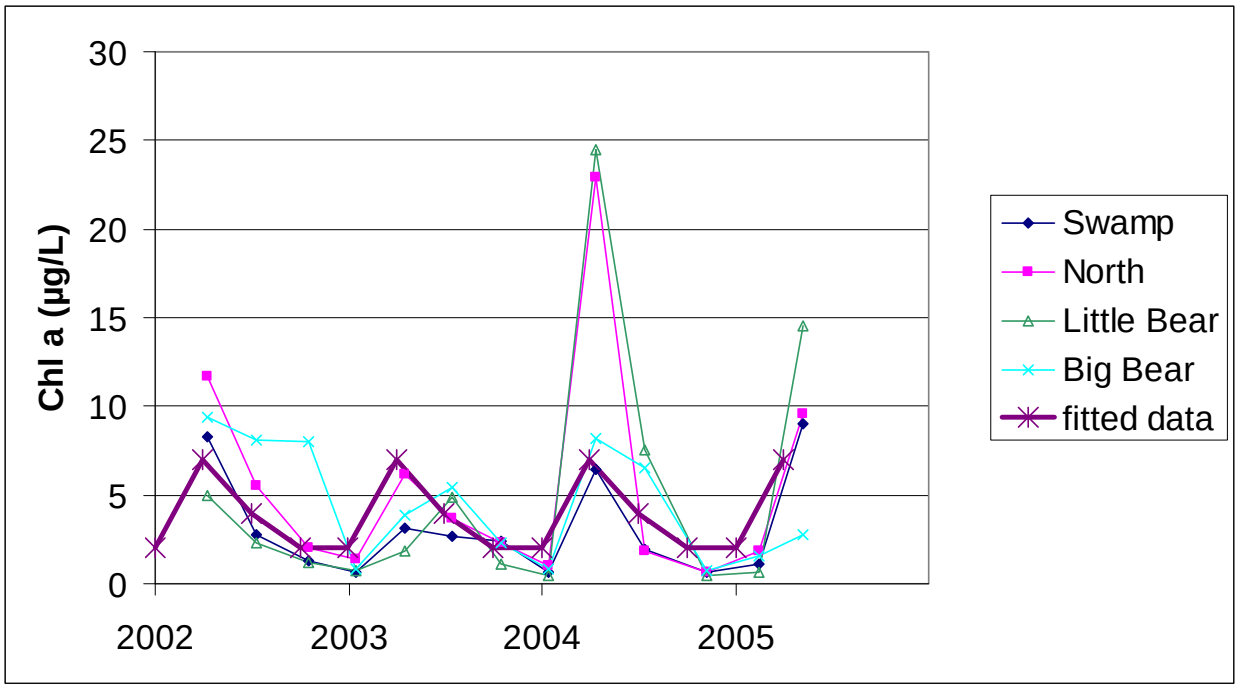


Figure 37 Chlorophyll *a* data for Sammamish River tributaries and long-term approximation applied to all four tributaries ("fitted data" above) used in model.

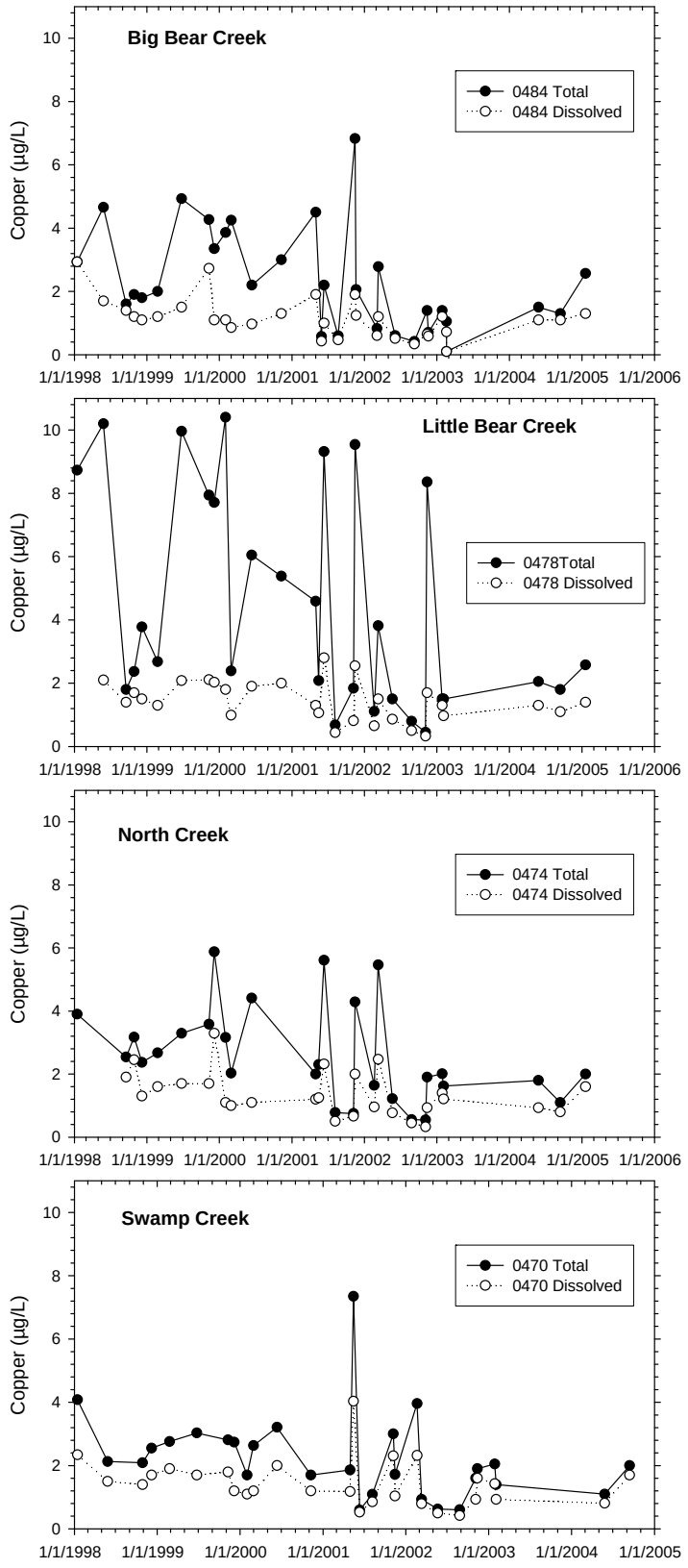


Figure 38 Total and dissolved copper concentrations in Sammamish River tributaries.

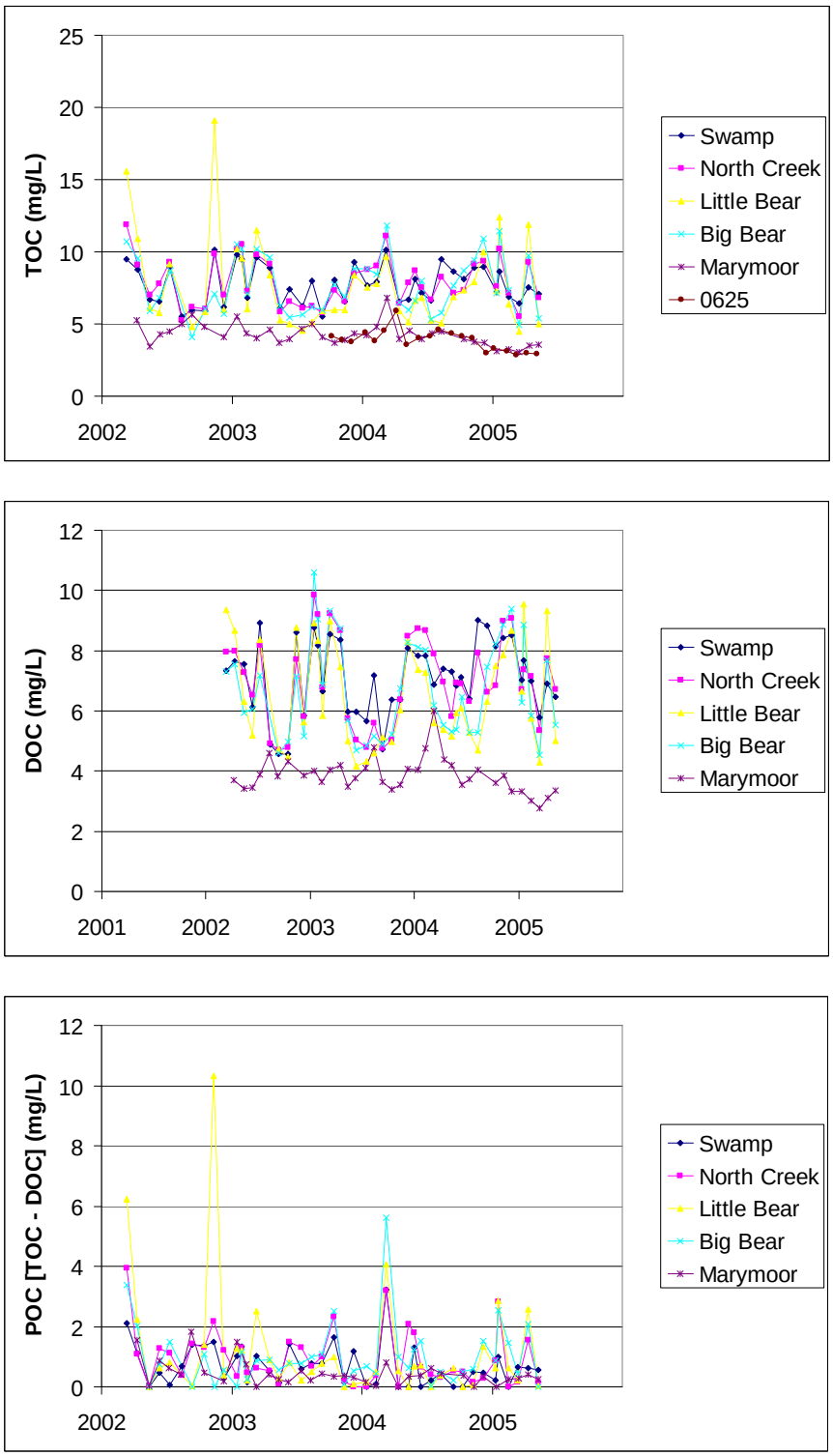


Figure 39 Available TOC, DOC and POC (TOC minus DOC) data for Sammamish River tributaries and the Sammamish River at Marymoor (0486).

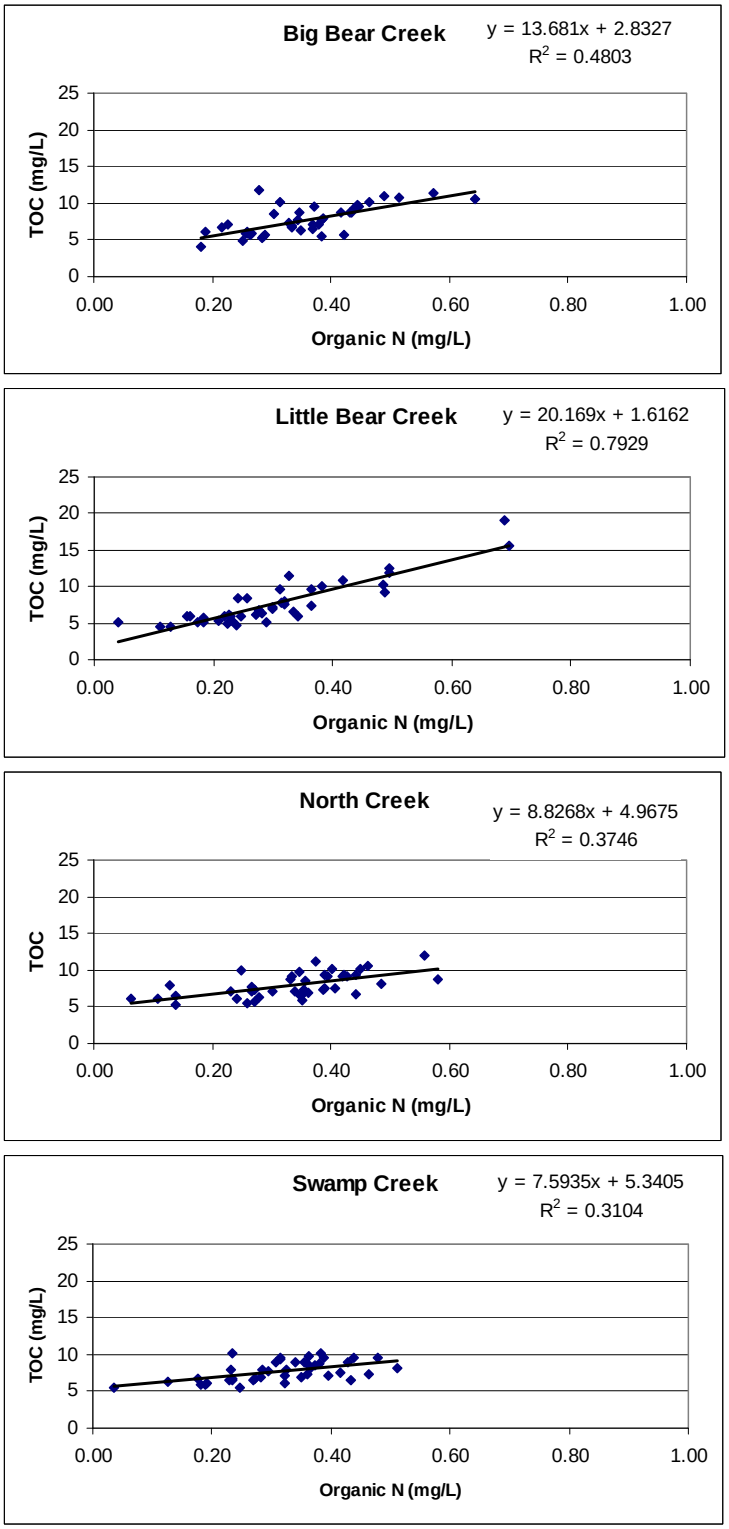


Figure 40 Linear regression results for Sammamish River tributary TOC vs. Organic N.

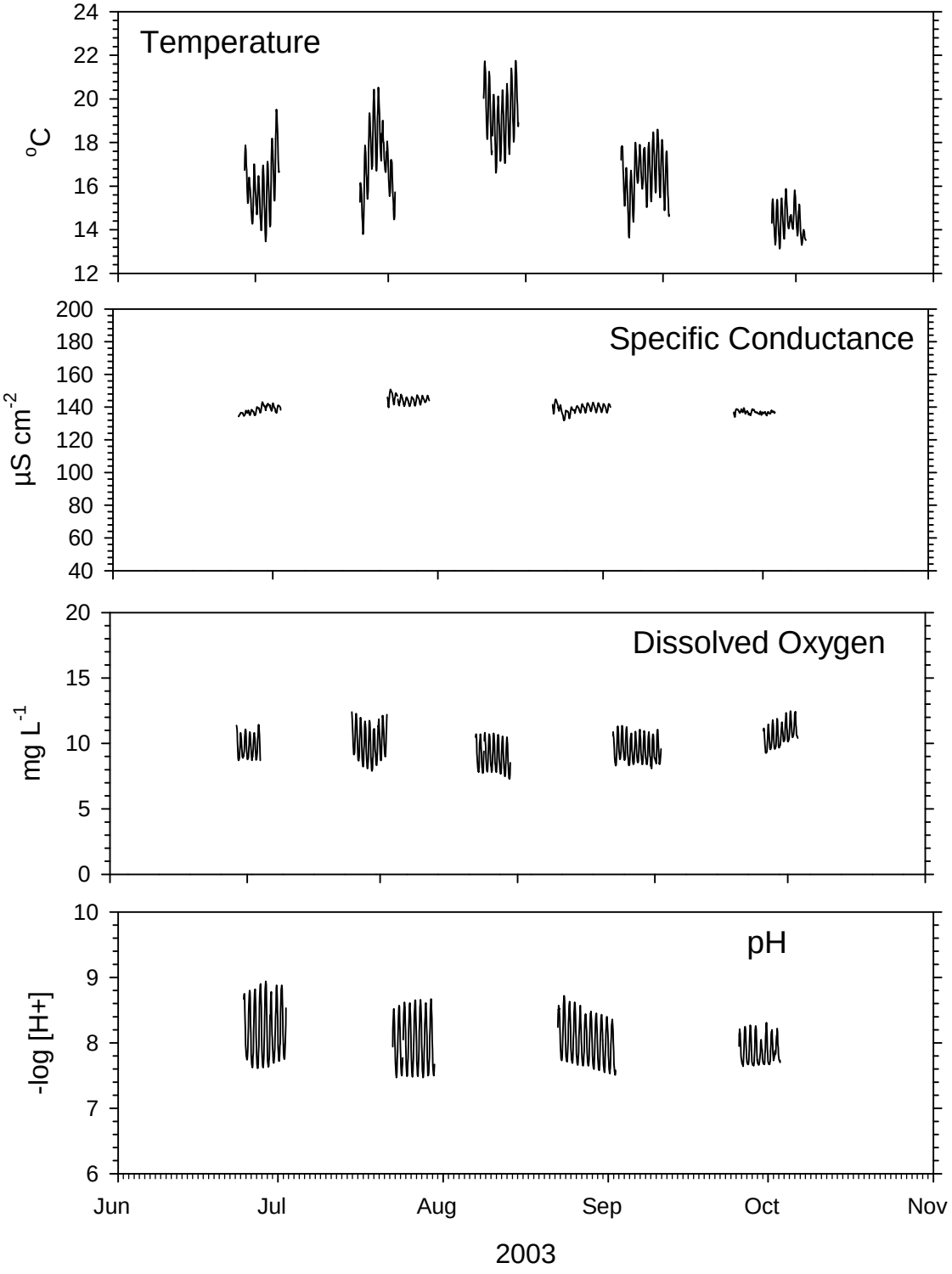


Figure 41 Continuous (hourly) sonde data collected near the mouth of Big Bear Creek during summer, 2003 (see King County 2005b for details).

As in the development of the Lake Sammamish water quality model (King County 2008), log-linear regression equations were used to develop higher frequency (in this case hourly) TSS, TP, and FC (and *E. coli*), and total copper concentrations for creation of tributary constituent inputs. The log-linear regression approach is described in more detail in Appendix A. Example regression results for Bear Creek are provided in Figure 42. The required model constituents and transformation steps are documented in Table 6 and Figure 28.

In order to facilitate comparison of constituent inputs from the upstream boundary and tributaries to the river, model input flow and constituent concentrations were converted to loading estimates. The estimated average loads of TP, SRP, TN, dissolved inorganic N (NO3-N + TNH3-N), TSS, TDS, TOC, DOC, FC and *E. coli* to the river are shown in Table 7. The relative loads from each surface water input to the river averaged over the model simulation period (1995-2003) are shown in Figure 43 and Figure 44.

4.3.2.3 In-stream Calibration Data

Routine water quality monitoring data collected by King County are available for model calibration from 5 locations between the upstream and downstream model boundary. Data are available from the NE 124th St (0450C) and Bothell Landing (0450A) stations since February 2000 and at the Sammamish River below Big Bear (0450D), Sammamish River above Little Bear (0450BB) and the Sammamish River above North Creek (0450B) stations since August 2002 (see Table 4 and Figure 17). Data for dissolved silica and TOC/DOC are only available beginning in August 2002. Because copper was not selected as a model parameter until after the additional sampling locations and parameters were suggested, limited total and dissolved copper data were collected in the Sammamish River as part of the Freshwater Program. However, eight mainstem stations were sampled at least once per year in 2001-2004, primarily as part of an assessment conducted for King County's Water Reuse Program (King County, 2005a). Infrequent sampling at stations 0450A and 0450C have continued through 2007. Available routine data for model calibration are shown in Figure 45 through Figure 55.

In the summer of 2003, continuous DO, pH and specific conductance and temperature data were collected at 6 locations along the river mainstem as part of a special study (King County 2005b). These data were used to test model performance in 2003, with an emphasis on the parameterization of submerged aquatic plant growth. The data available for model calibration are shown in Figure 56 through.Figure 59.

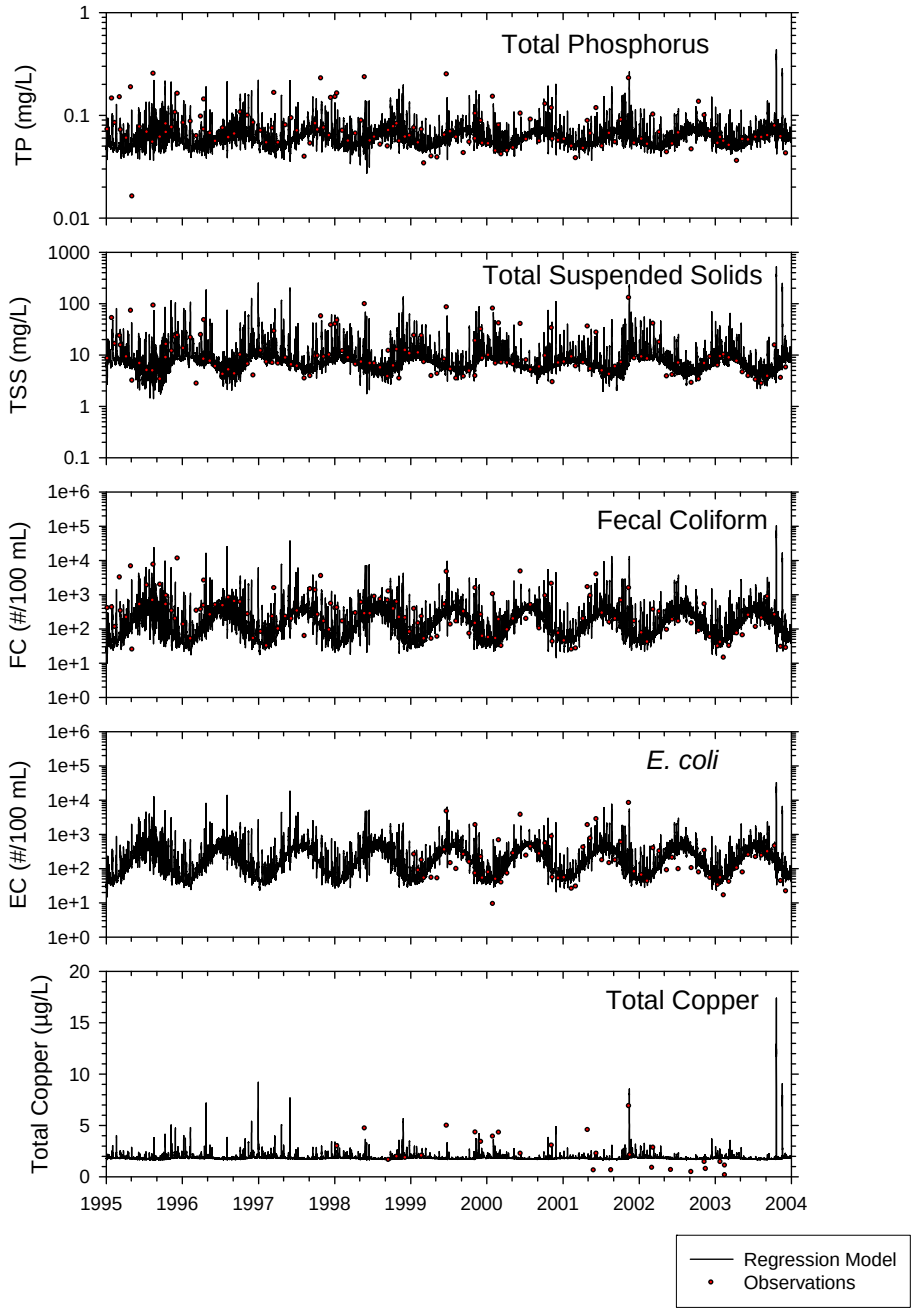


Figure 42 Log-linear TP, TSS, FC, EC and total copper regression results for Big Bear Creek.

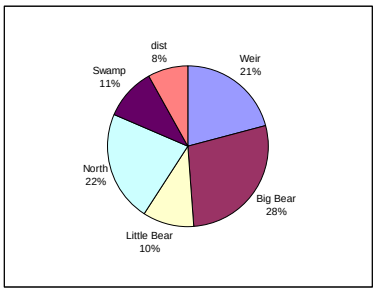
Table 7. Estimated average constituent loads to the Sammamish River, 1995-2003.

Basin	TP	SRP	TN	DIN	TSS	TDS	TOC	DOC	Total Cu	FC	*E. coli*
	kg yr^{-1}									10^6 yr^{-1}	
Lake Sammamish	4174	1247	93209	53983	609136	9900835	801745	721571	107	5.5E+07	8.9E+07
Big Bear	5619	2025	83873	55032	1062315	4101121	591877	532689	144	2.4E+08	1.8E+08
Little Bear	2019	640	32350	24543	960836	1526181	194351	174916	94	4.8E+08	3.3E+08
North	4456	1829	67497	48157	733966	3982797	425491	382942	105	4.1E+08	3.6E+08
Swamp	2112	842	45334	33784	415022	2782984	265370	238833	62	3.0E+08	1.5E+08
Distributed	1626	509.6	26007	19627	886769	1210118	158069	142262	78	4.7E+08	3.1E+08

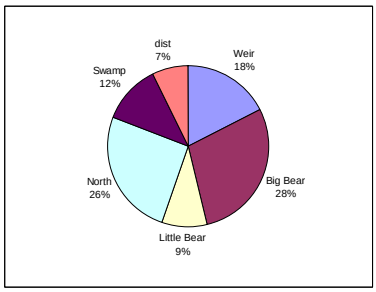
Table 8. Estimated average constituent yield to the Sammamish River, 1995-2003.

Basin	TP	SRP	TN	DIN	TSS	TDS	TOC	DOC	Total Cu	FC	*E. coli*
	kg km^{-2} yr^{-1}									10^6 km^{-2} yr^{-1}	
Lake Sammamish	16.6	5.0	371.4	215.1	2427	39446	3194	2875	0.43	2.2E+05	3.6E+05
Big Bear	22.4	8.1	334.2	219.3	4232	16339	2358	2122	0.57	9.5E+05	7.0E+05
Little Bear	8.0	2.5	128.9	97.8	3828	6080	774	697	0.37	1.9E+06	1.3E+06
North	17.8	7.3	268.9	191.9	2924	15868	1695	1526	0.42	1.6E+06	1.4E+06
Swamp	8.4	3.4	180.6	134.6	1653	11088	1057	952	0.25	1.2E+06	5.8E+05
Distributed	6.5	2.0	103.6	78.2	3533	4821	630	567	0.31	1.9E+06	1.2E+06

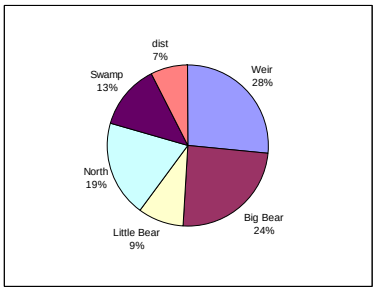
Total Phosphorus



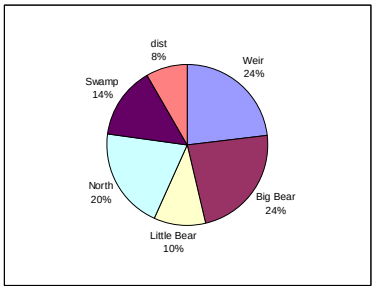
Soluble Reactive Phosphorus



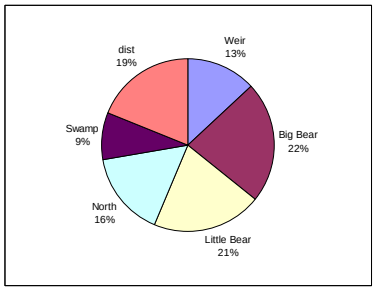
Total Nitrogen



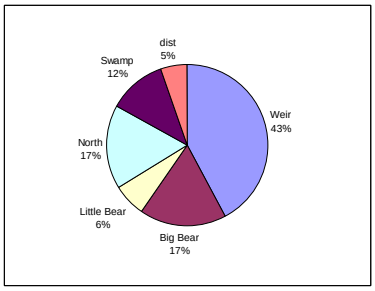
Dissolved Inorganic Nitrogen



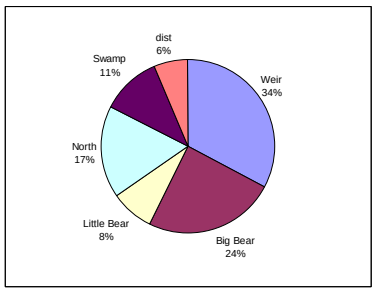
Total Suspended Solids



Total Dissolved Solids



Total Organic Carbon



Total Copper

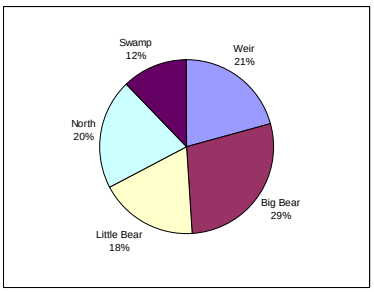


Figure 43 Summary of relative model-specified TP, SRP, TN, DIN, TSS, TDS, TOC, and total copper contributions from the upstream boundary, major tributaries and distributed tributary inputs to the Sammamish River, 1995-2003.

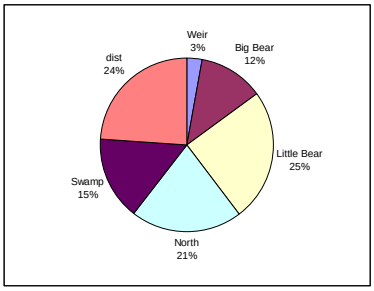
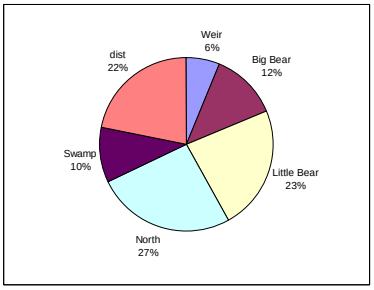
Fecal Coliform	***E. coli***
	

Figure 44 Summary of relative model-specified fecal coliform and *E. coli* contributions from the upstream boundary, major tributaries and distributed tributary inputs to the Sammamish River, 1995-2003.

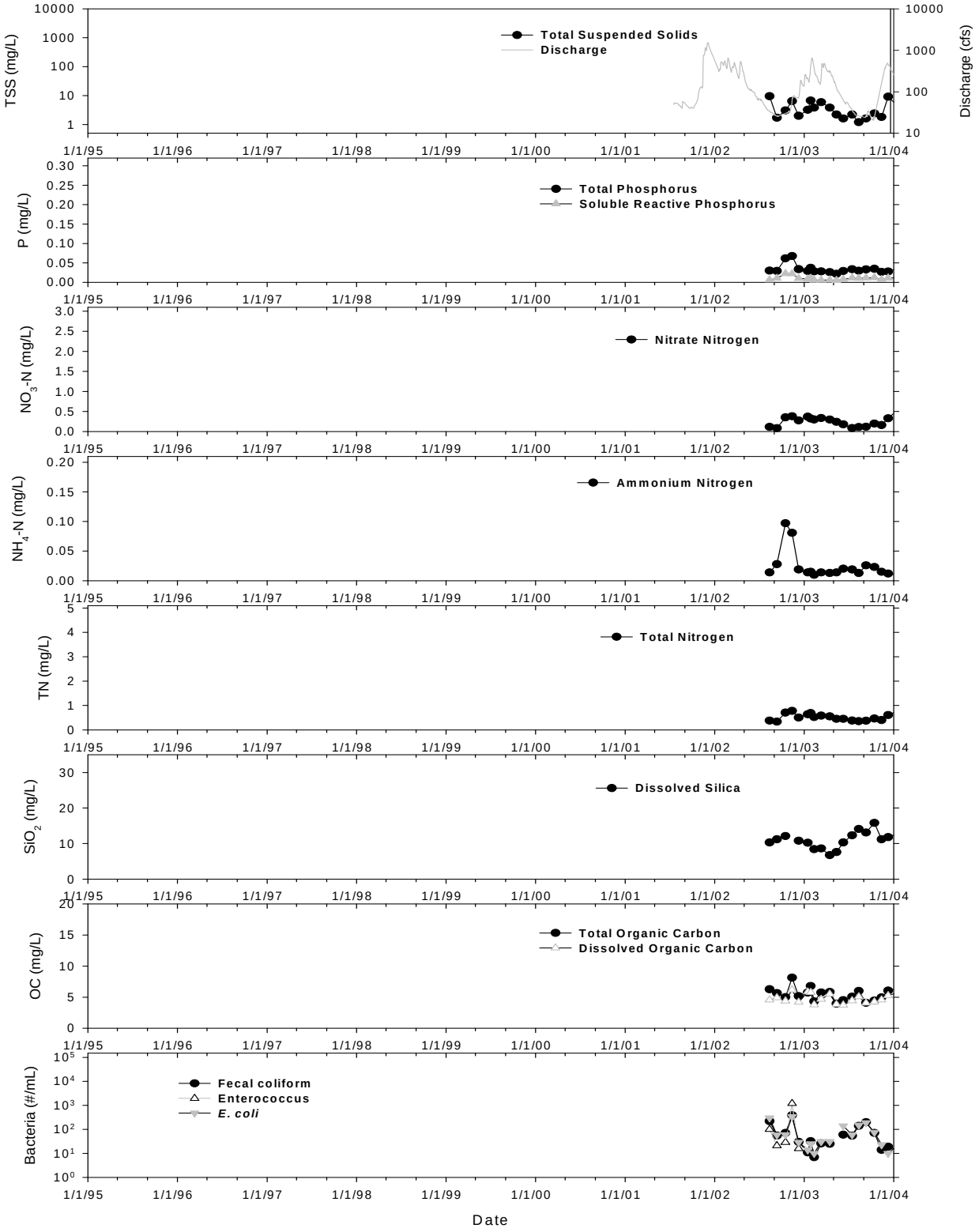


Figure 45 Water quality data for Sammamish River below Big Bear Creek (0450D), 2002-2003. All discharge data from King County gauge (51m).

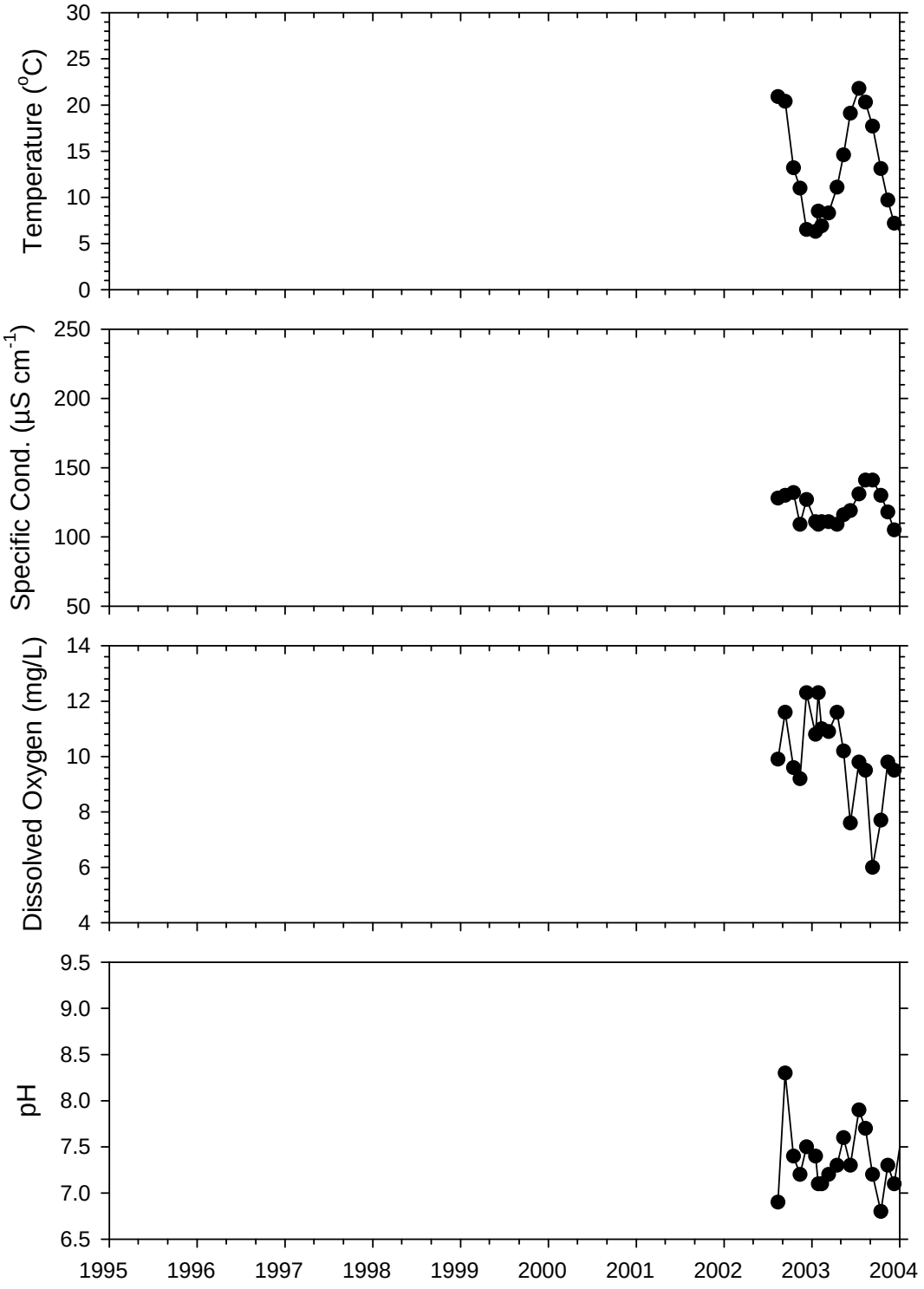


Figure 46 Temperature, conductance, DO and pH data for Sammamish River below Big Bear Creek (0450D), 2002-2003.

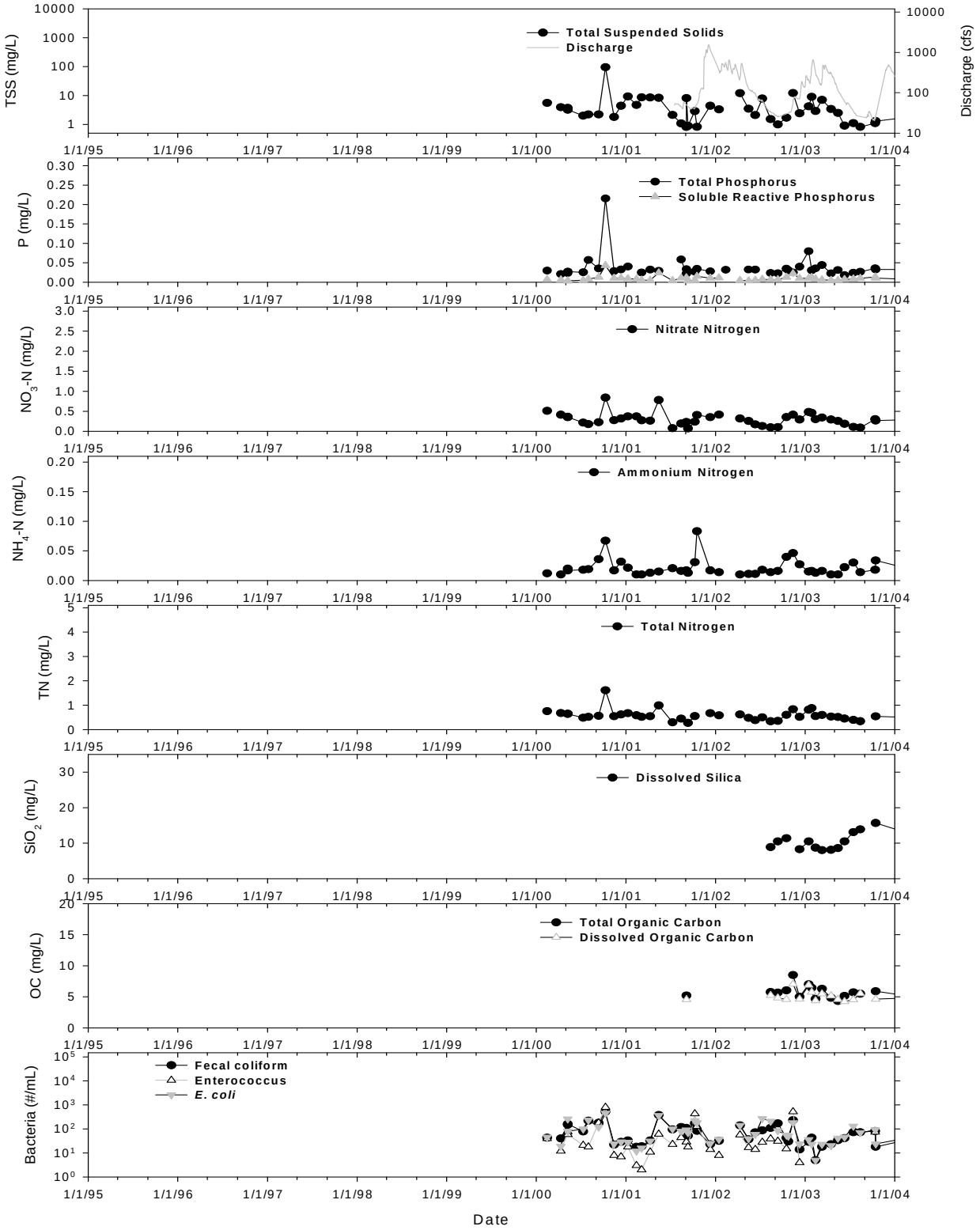


Figure 47 Water quality data for Sammamish River at NE 124th St Bridge (0450C), 2000-2003. All discharge data from King County gauge (51m).

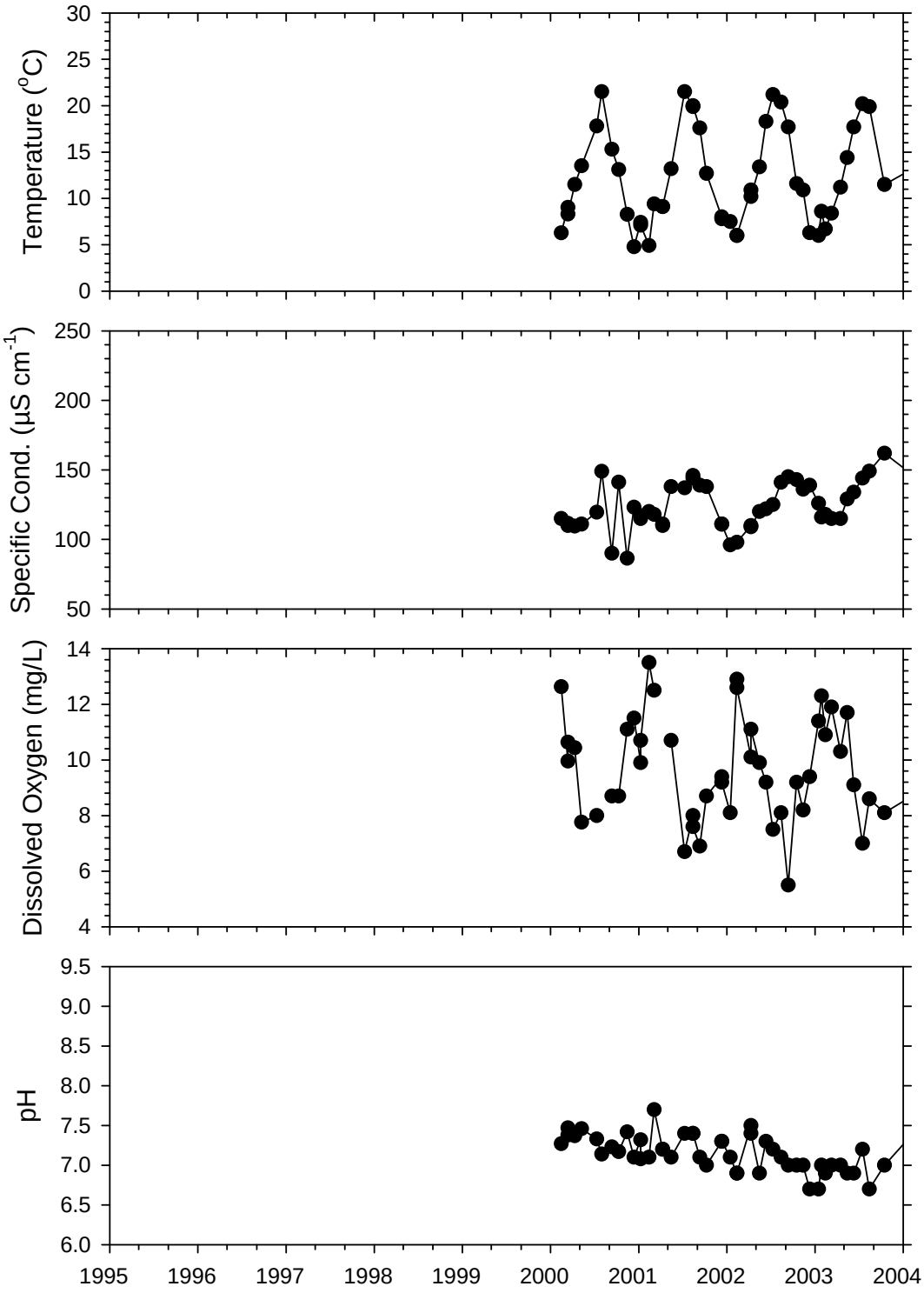


Figure 48 Temperature, conductance, DO and pH data for Sammamish River at NE 124th St Bridge (0450C), 2000-2003.

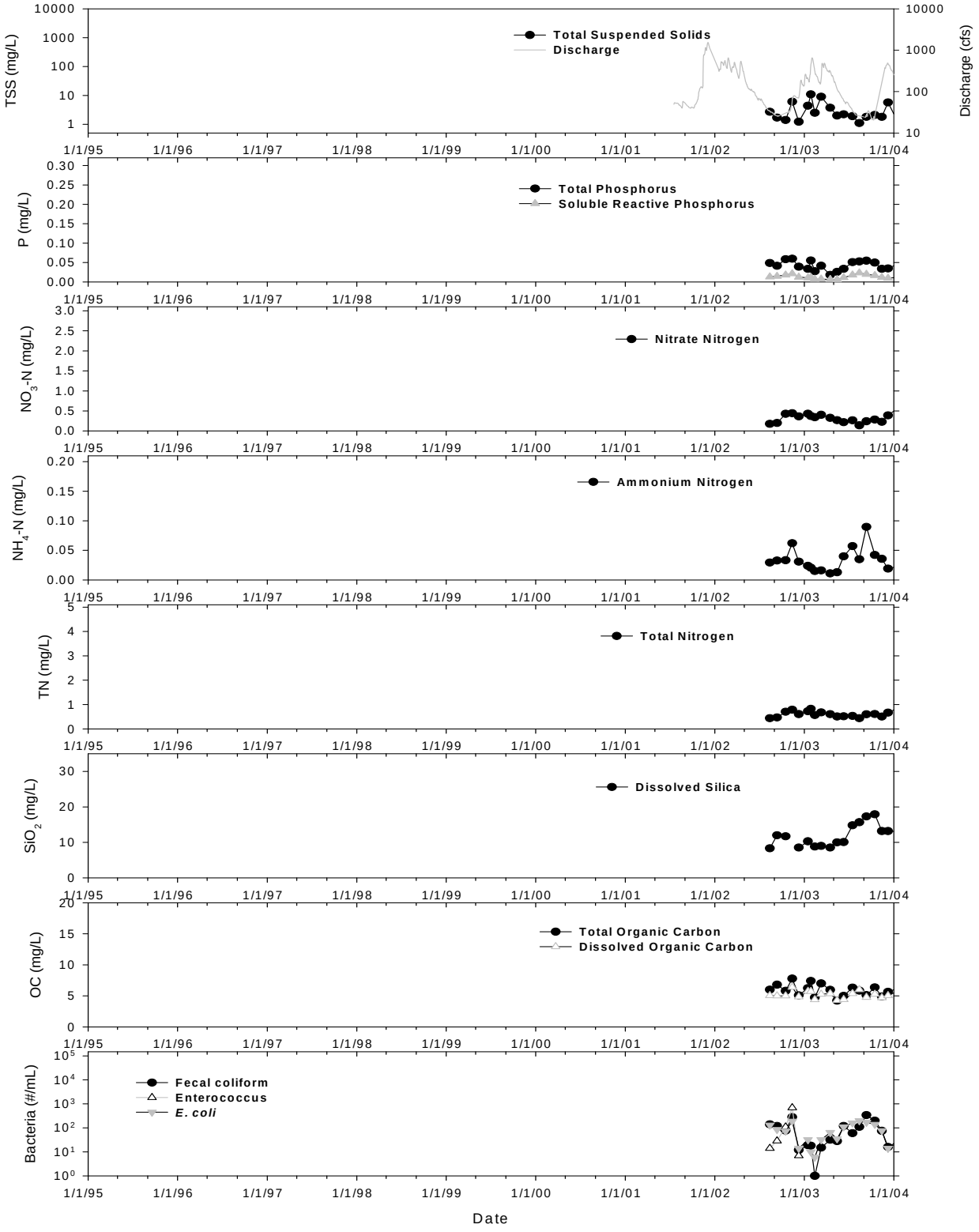


Figure 49 Water quality data for Sammamish River above Little Bear Creek (0450BB), 2002-2003. All discharge data from King County gauge (51m).

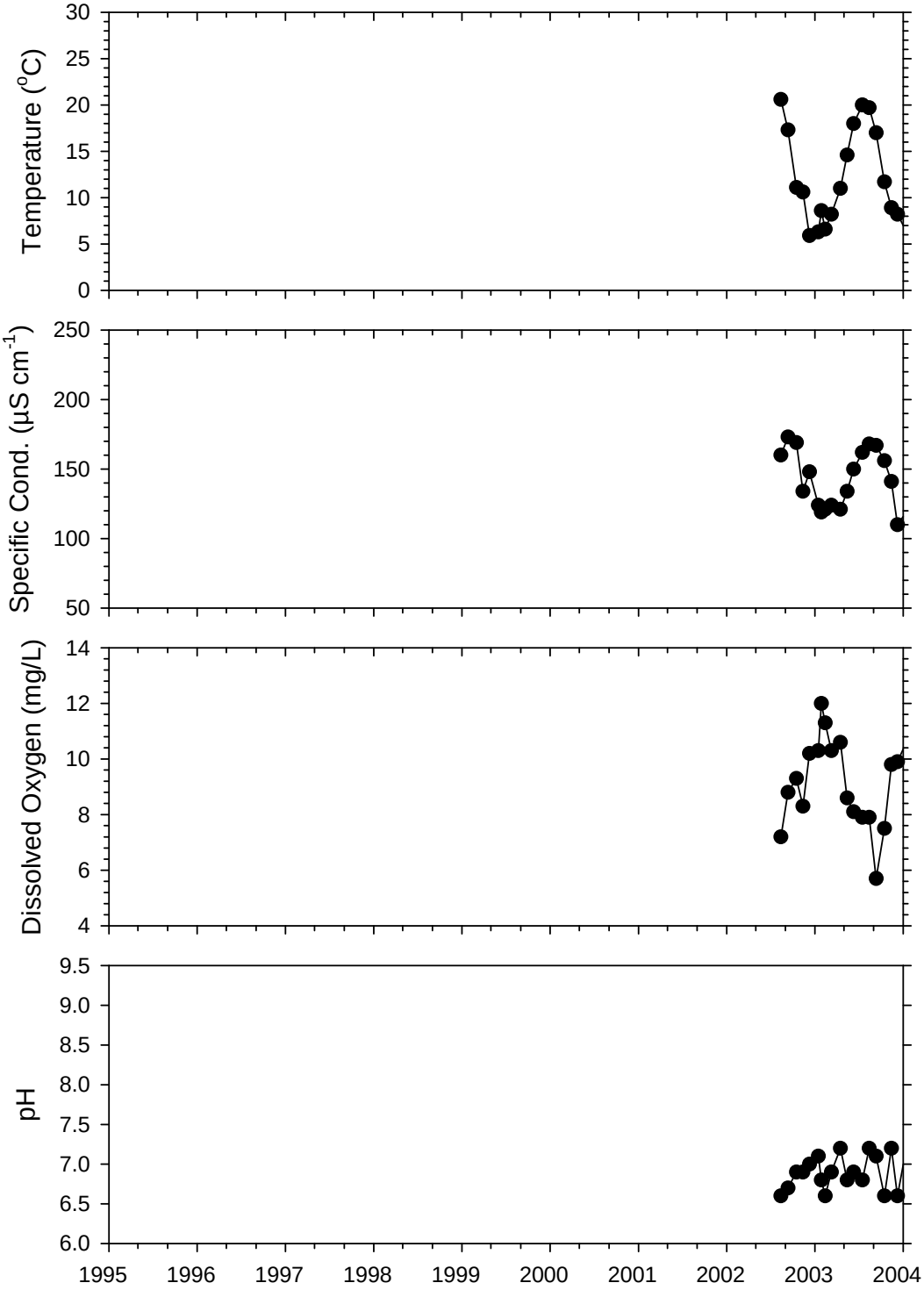


Figure 50 Temperature, conductance, DO and pH data for Sammamish River above Little Bear Creek (0450BB), 2002-2003.

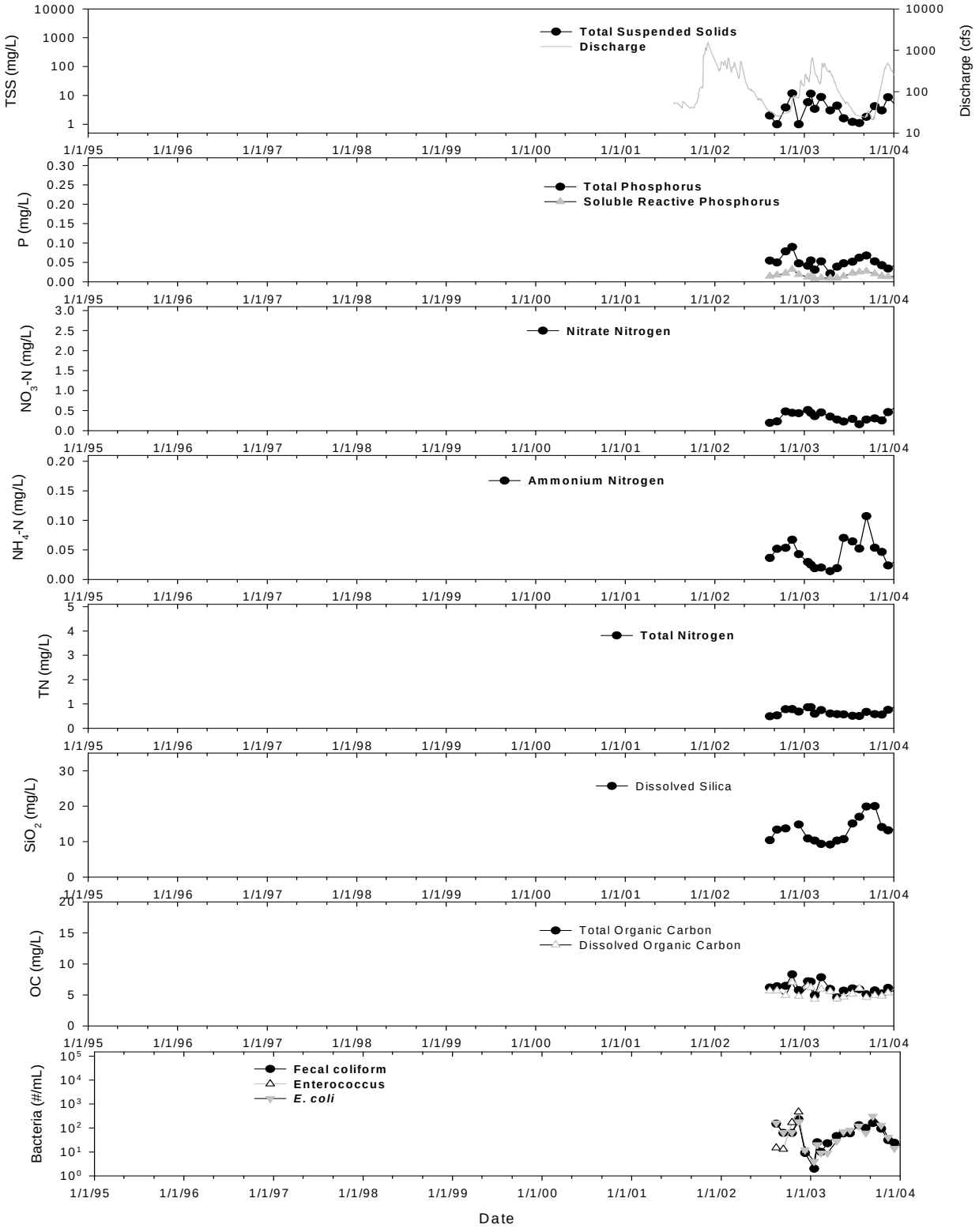


Figure 51 Water quality data for Sammamish River above North Creek (0450B), 2002-2003. All discharge data from King County gauge (51m).

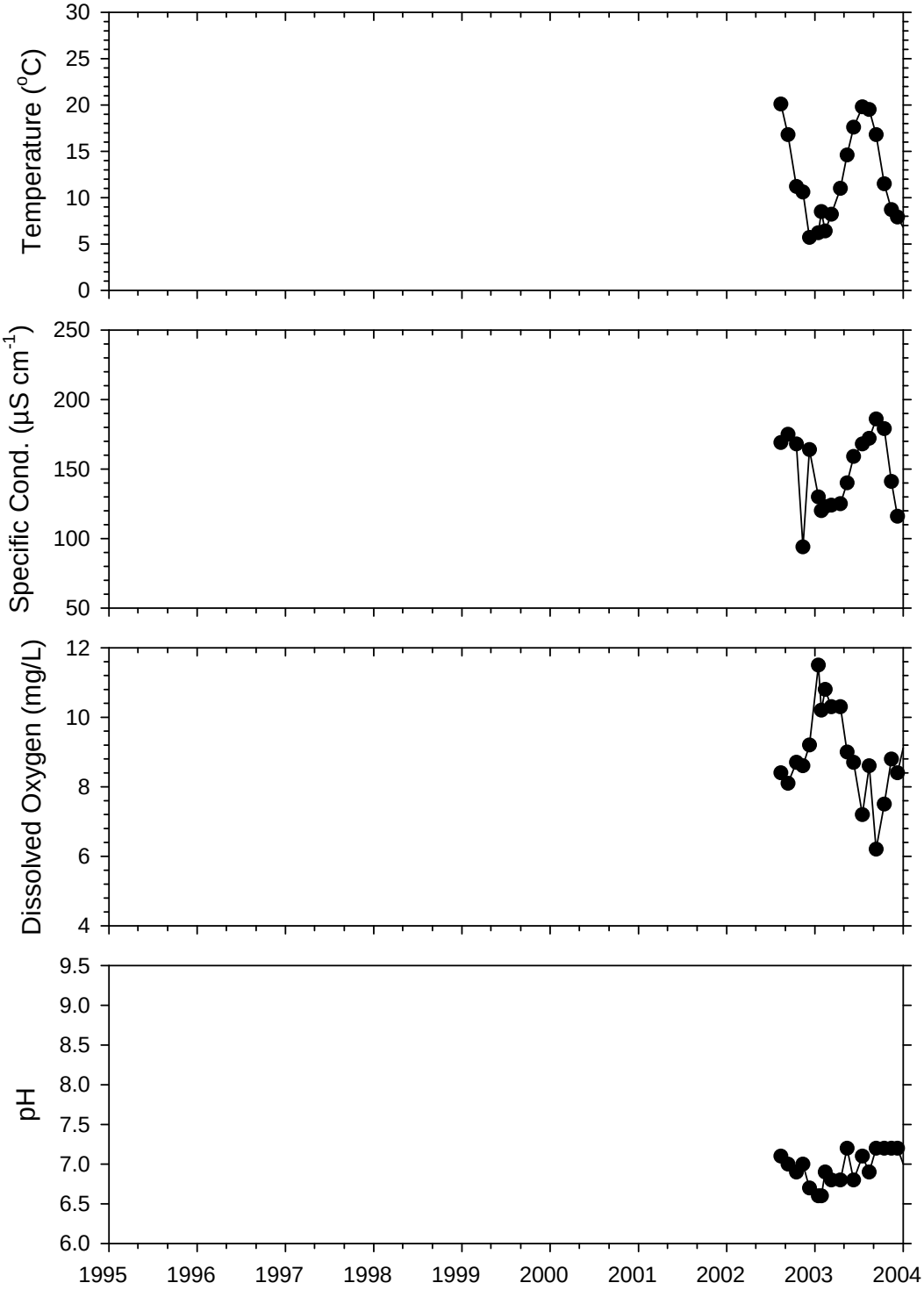


Figure 52 Temperature, conductance, DO and pH data for Sammamish River above North Creek (0450B), 2002-2003.

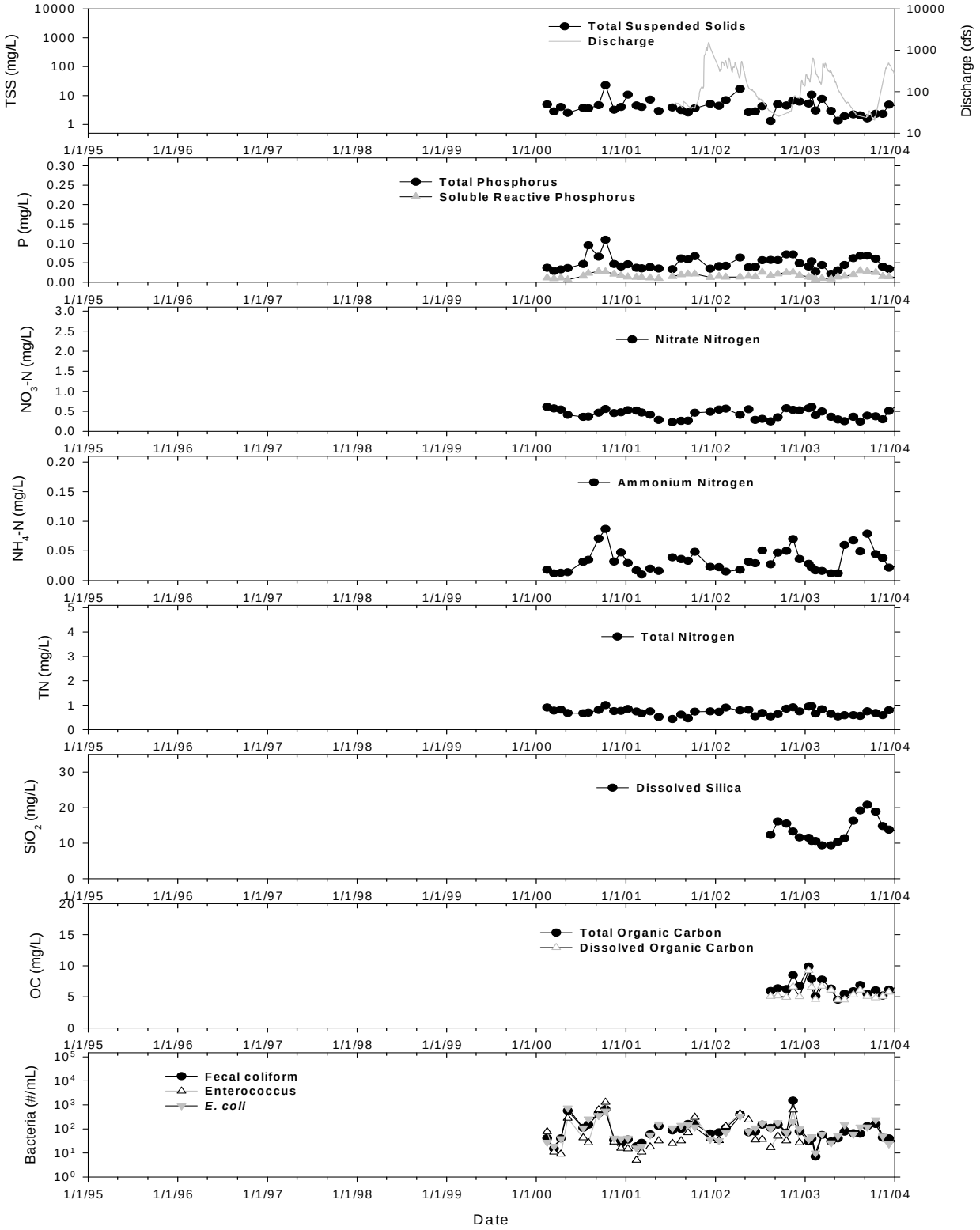


Figure 53 Water quality data for Sammamish River at Bothell Landing (0450A), 2000-2003. All discharge data from King County gauge (51m).

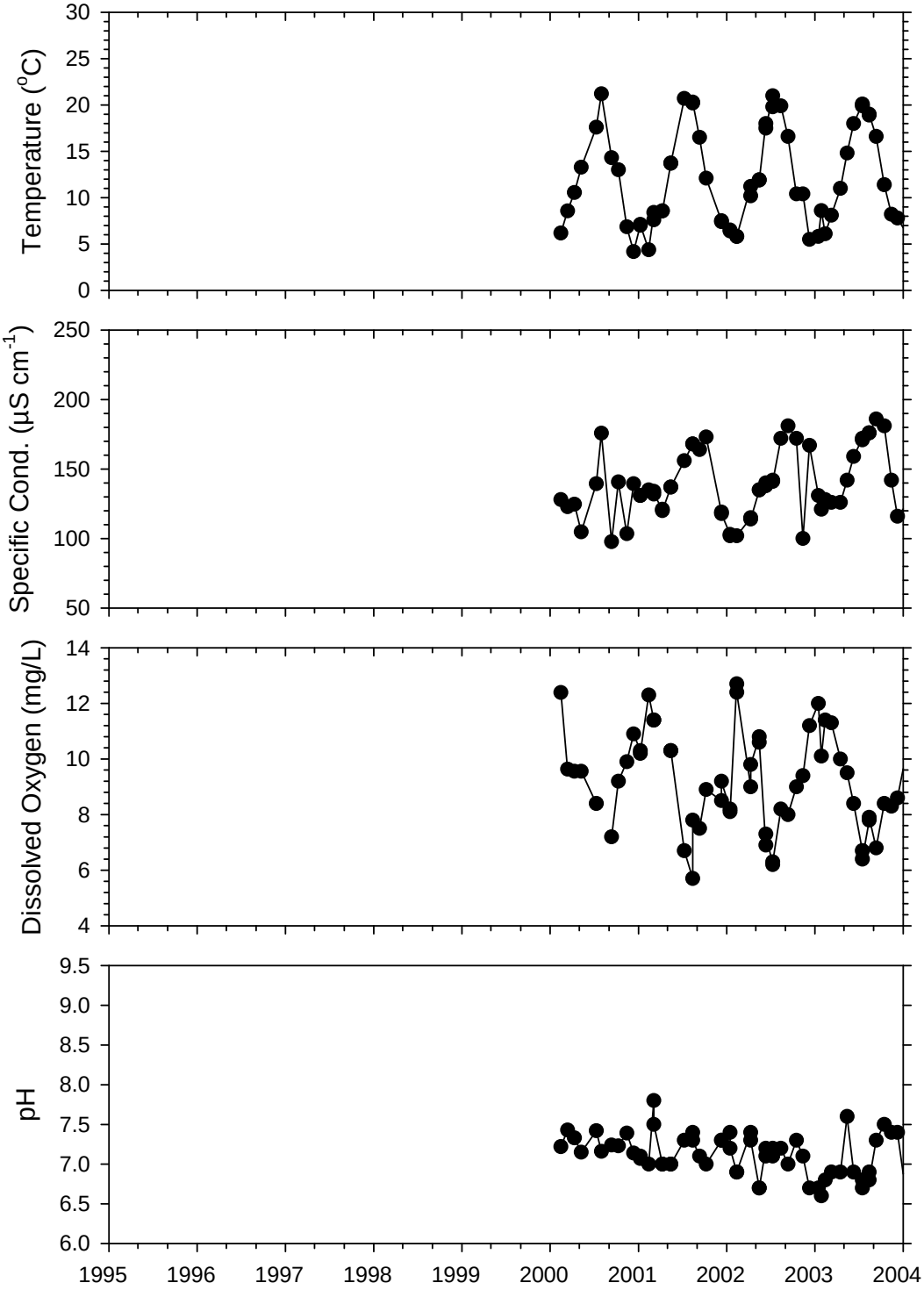


Figure 54 Temperature, conductance, DO and pH data for Sammamish River at Bothell Landing (0450A), 2000-2003.

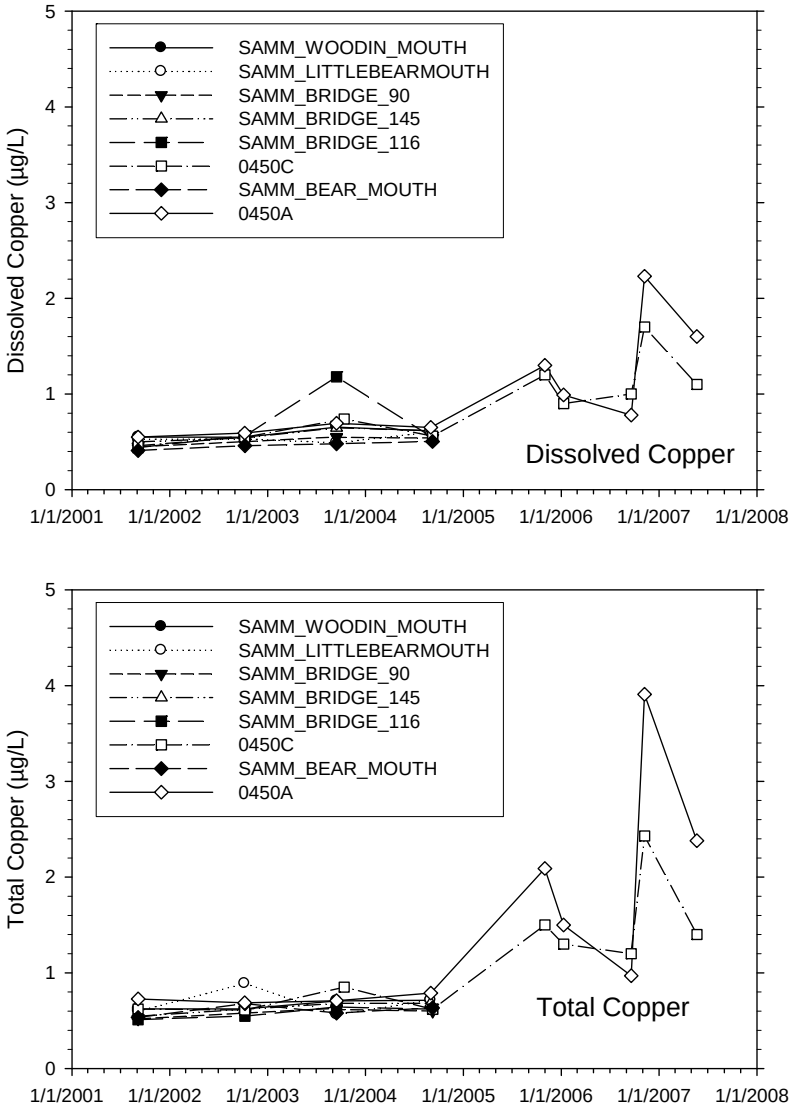


Figure 55 Available total and dissolved copper data for Sammamish River mainstem locations, 2001-2007.

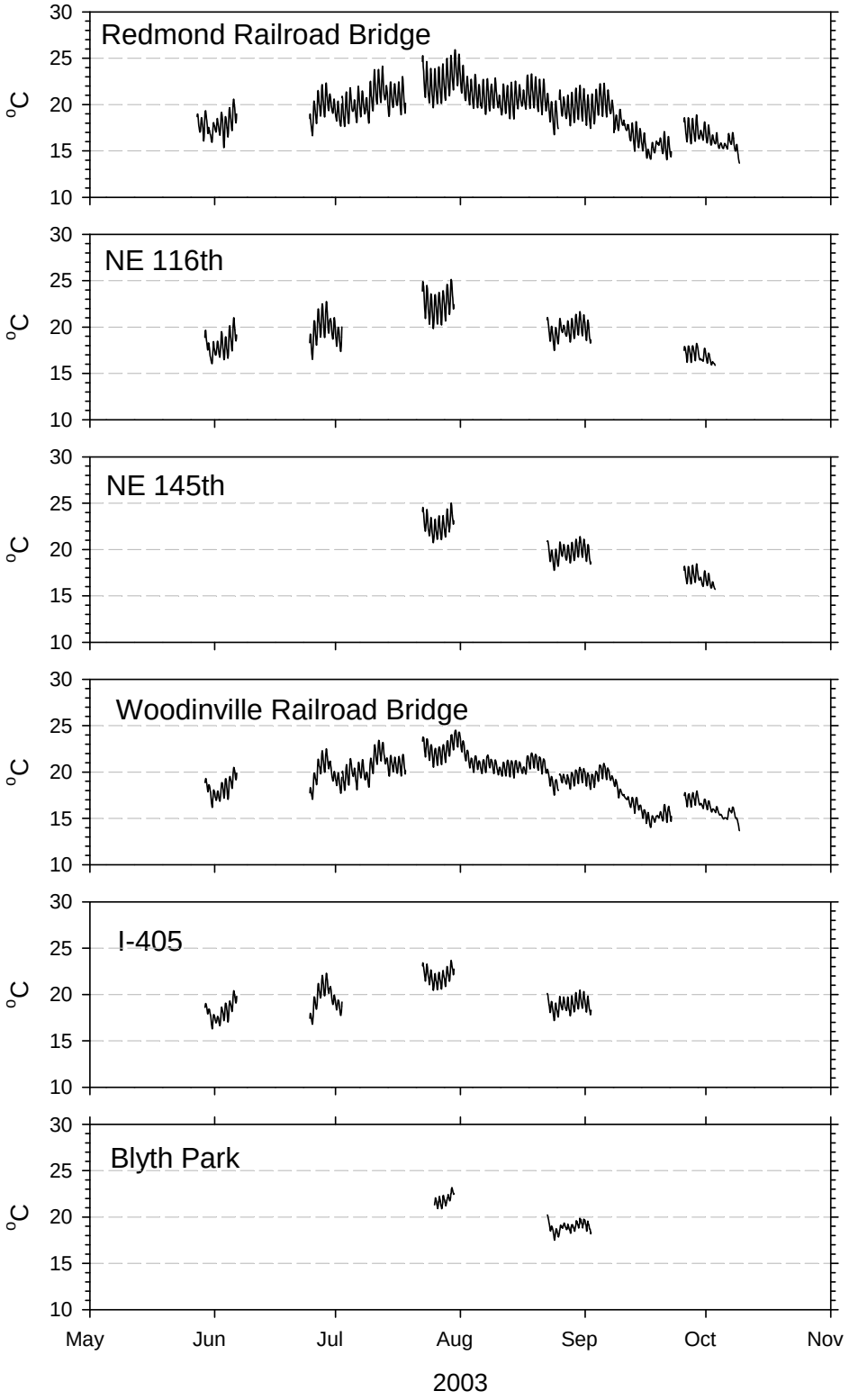


Figure 56 Continuous (hourly) sonde temperature data collected at 6 locations along the Sammamish River in summer, 2003 (see King County 2005b for details).

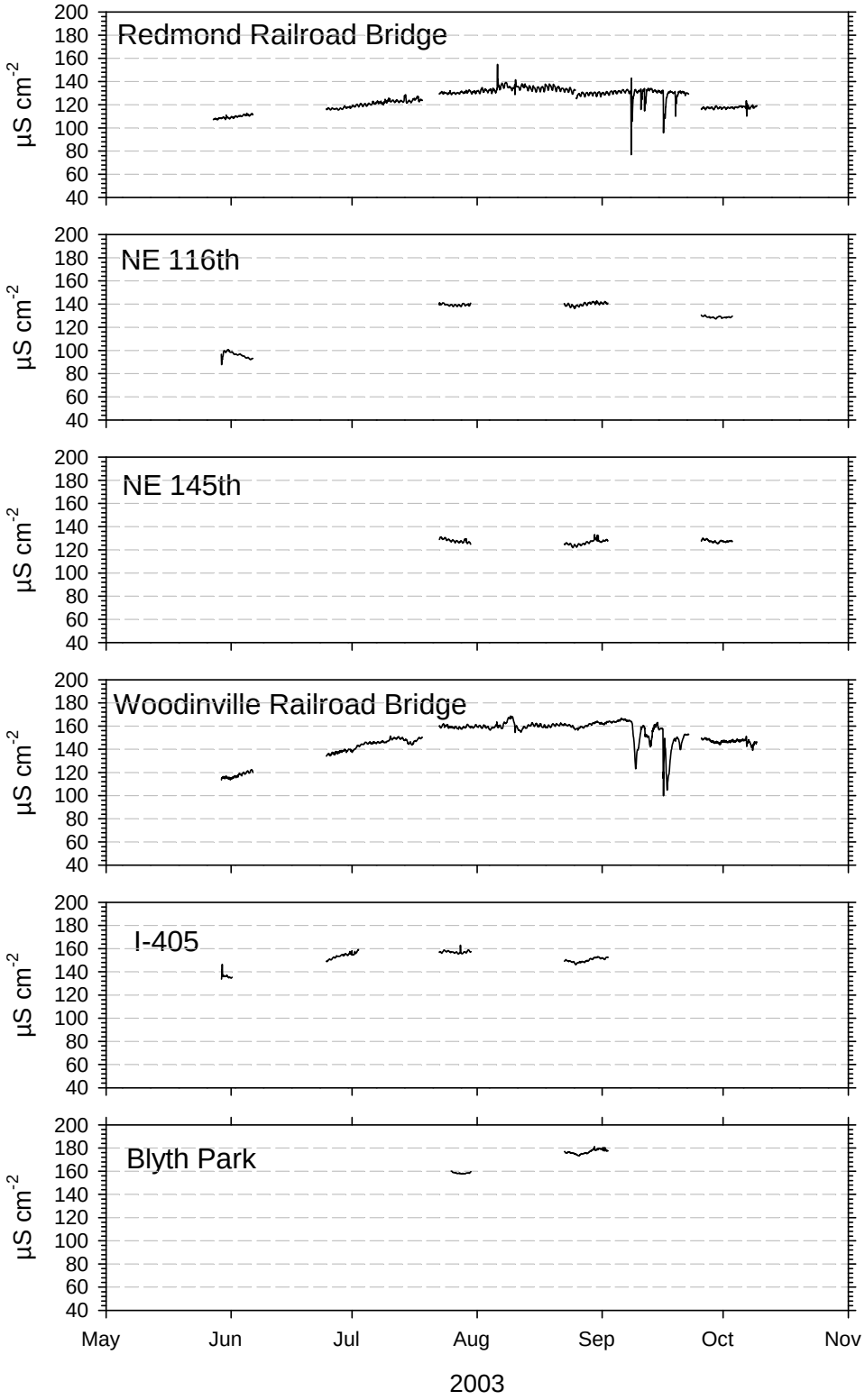


Figure 57 Continuous (hourly) sonde specific conductance data collected at 6 locations along the Sammamish River in summer, 2003 (see King County 2005b for details).

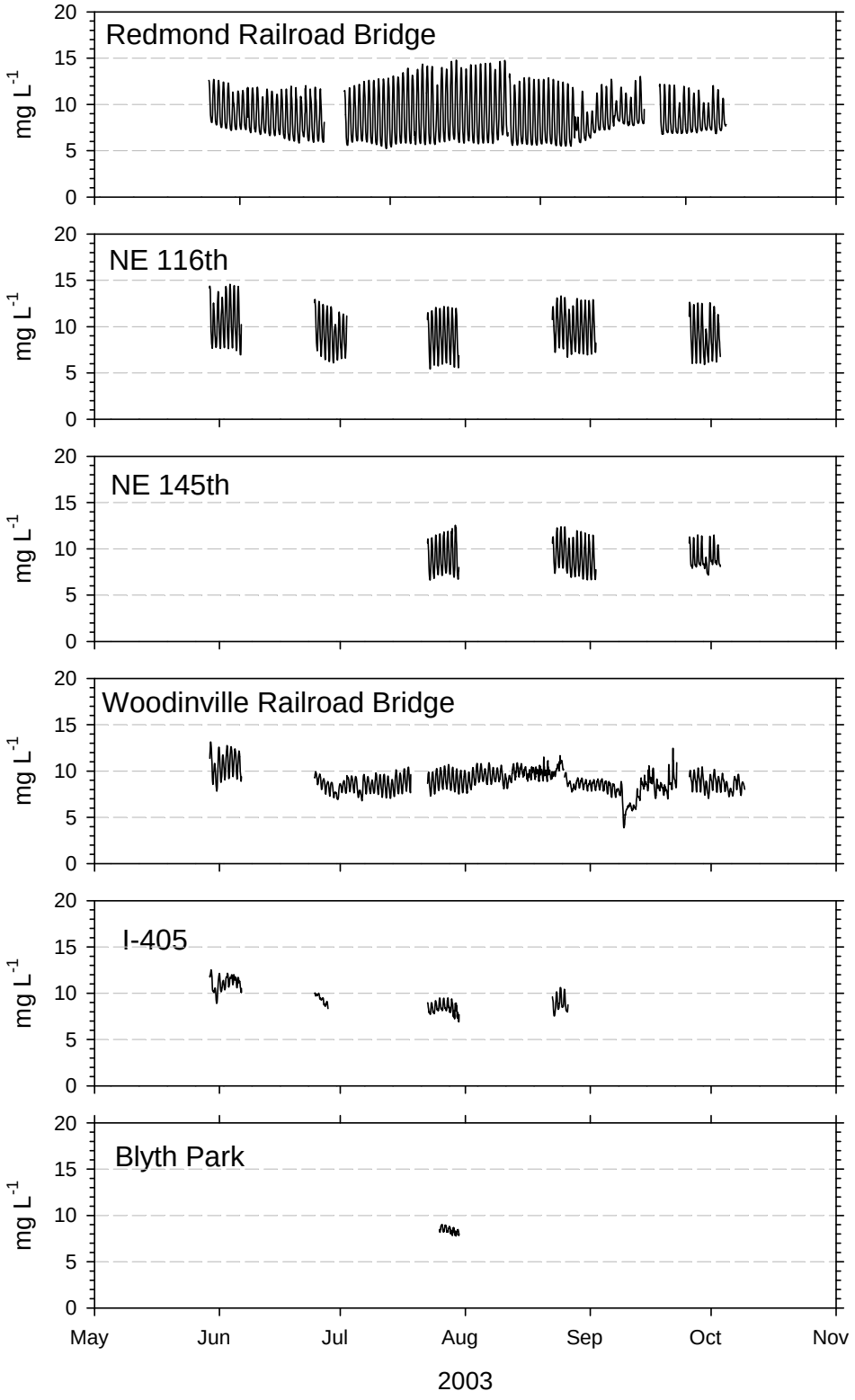


Figure 58 Continuous (hourly) sonde dissolved oxygen data collected at 6 locations along the Sammamish River in summer, 2003 (see King County 2005b for details).

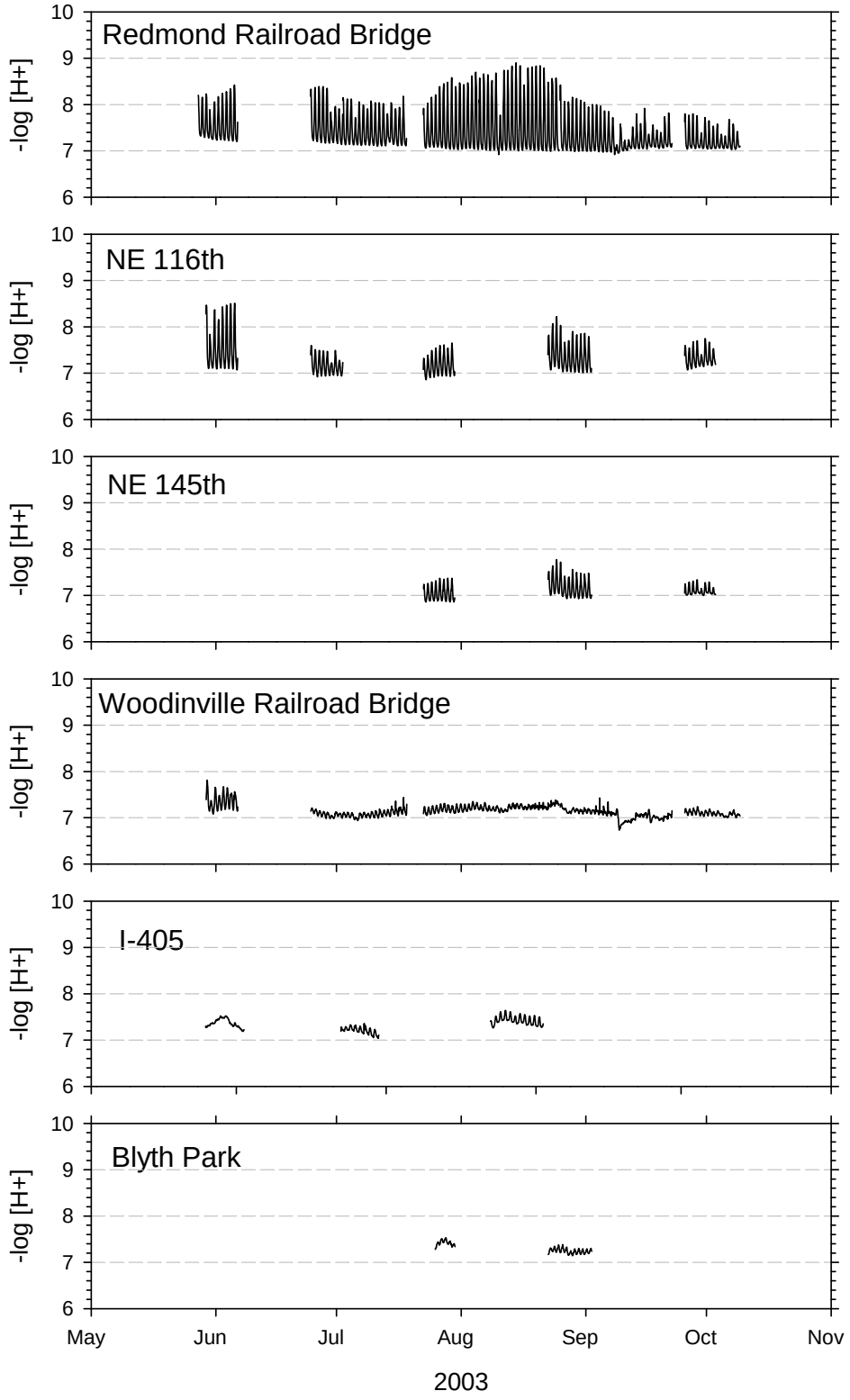


Figure 59 Continuous (hourly) sonde pH data collected at 6 locations along the Sammamish River in summer, 2003 (see King County 2005b for details).

4.3.2.4 Downstream Boundary

Downstream constituent boundary conditions were specified on a daily frequency using linear interpolation of depth-averaged routine water quality observations at Lake Washington station 0804 (see Table 4 and Figure 17). The required model constituents and transformation steps are documented in Table 6 and Figure 28. Available constituent data for the downstream boundary are shown in Figure 60 and available DO, pH, specific conductance and temperature data are shown in Figure 61. Available chlorophyll *a* data are shown in Figure 62.

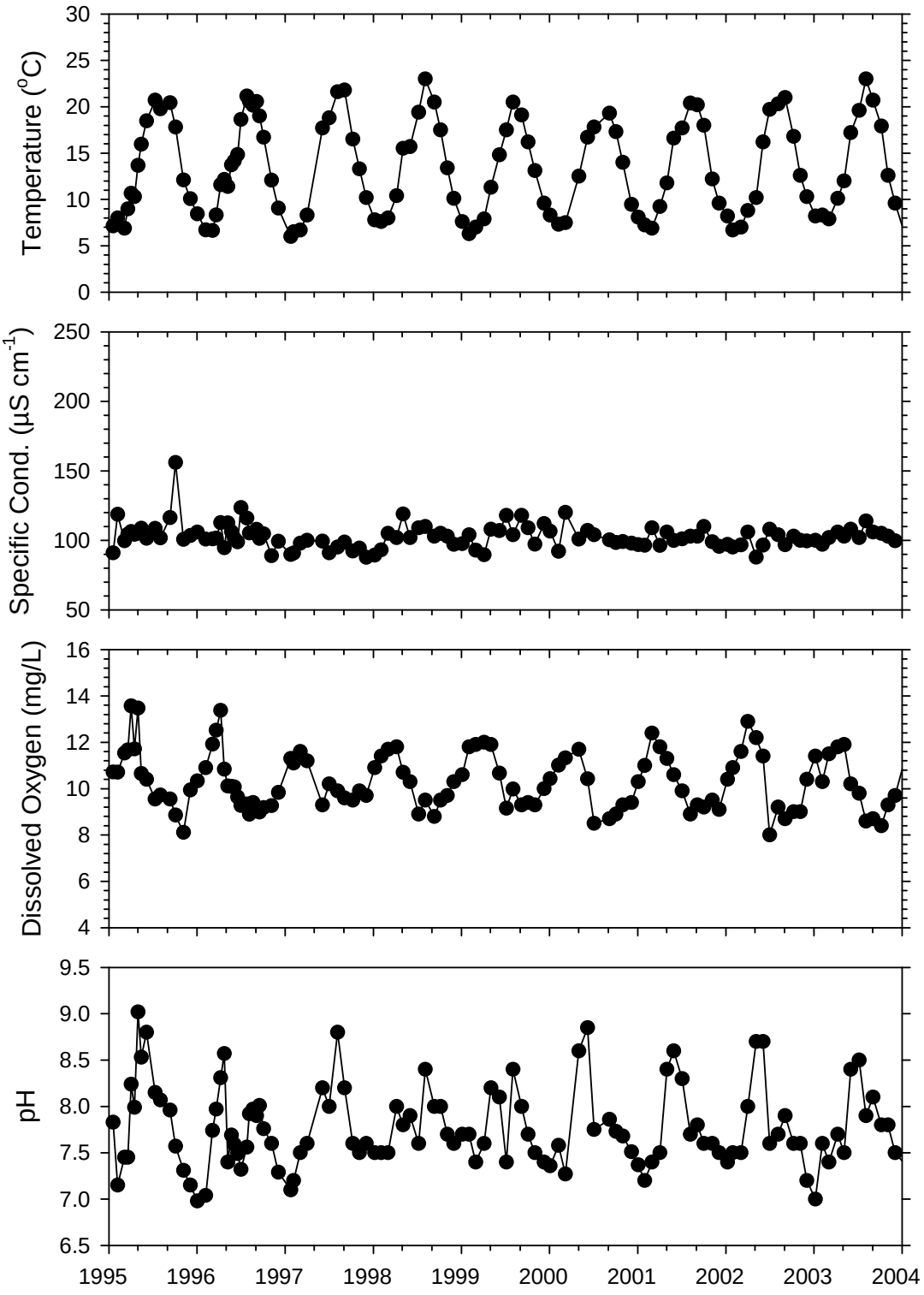


Figure 61 Temperature, conductance, DO and pH data for Lake Washington at Kenmore (0804), 1995-2003.

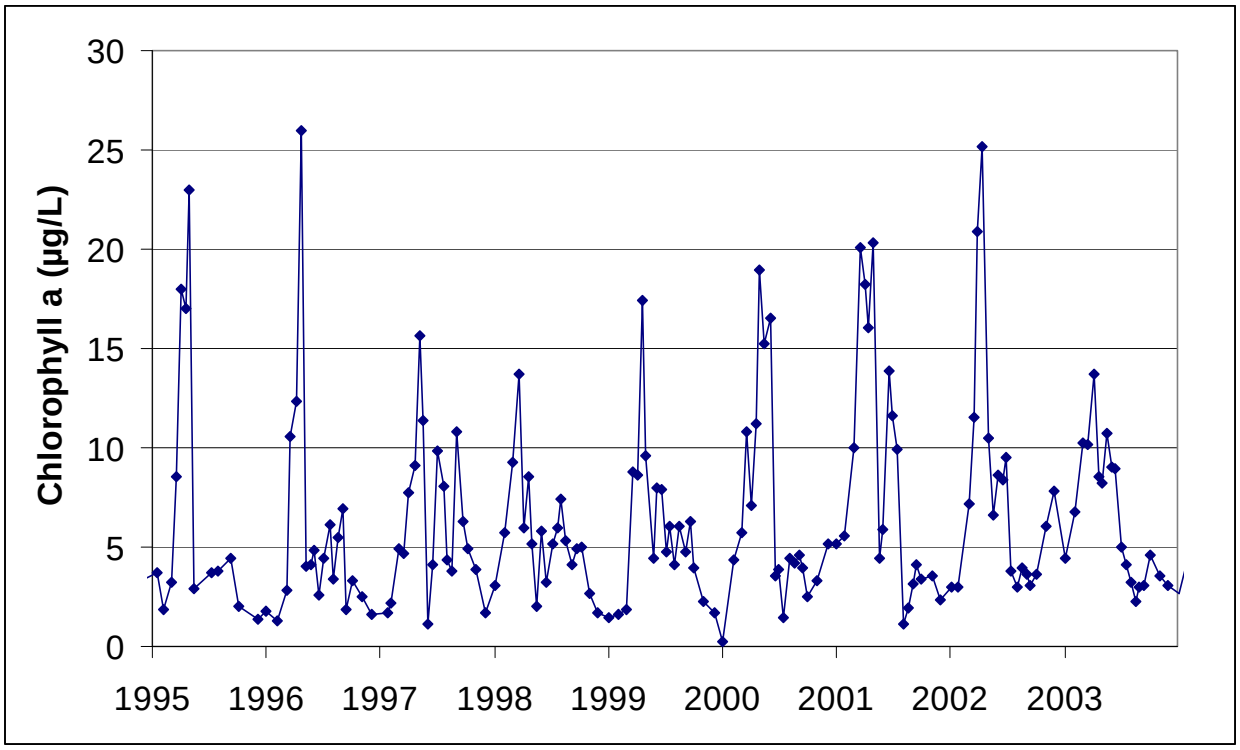


Figure 62 Chlorophyll *a* data for Lake Washington at Kenmore (0804), 1995-2003.

4.4 Meteorological Data

Hourly or more frequent observations of air temperature, dew point, wind speed, wind direction, cloud cover, and solar radiation are needed as inputs to the model. Because the Sammamish River is located on the fringe of the Seattle metropolitan area, meteorological data are available from a variety of locations (Table 9, Figure 63). Due to the length and quality of available records, data from Sea-Tac International Airport, approximately 30 km southwest of the Sammamish River is the primary source of meteorological model inputs. Solar radiation observations at Sea-Tac ended in 1990[10], but beginning in March 1995 observations were initiated at the NOAA Sandpoint Facility on the western shores of Lake Washington (approximately 9 km from the Sammamish River) as part of the Integrated Surface Irradiance Study (ISIS). The Atmospheric Science Department at the University of Washington (UW), located just west of Lake Washington (14 km from the Sammamish River) has also been measuring solar radiation – 1 minute data are available from their website beginning in July 1999. Sea-Tac meteorological data and solar radiation observations from UW and NOAA Sandpoint are currently used to provide meteorological inputs to the model.

[10] Hourly records for the period 1960-1990 are available from the National Climatic Data Center (NCDC) National Solar Radiation Database (NSRDB) and online at http://rredc.nrel.gov/solar/old_data/nsrdb/.

Table 9. Selected meteorological stations in the vicinity of Lake Sammamish.

Site Code	Site Name	Northing	Easting	Date Installed	Date Removed	Ground elevation in meters (NGVD 1929)
WBAN # 24233	Sea-Tac International Airport	167684 †	1273425 †	1-Nov-44	active	112.8 (4/2/02-) 121.9 (1/50-4/02)
SAMMS	Lake Sammamish RUSS buoy	215739	1329082	27-Jul-00	**active**	8.0
UW	University of Washington Atm. Sci. Bldg.	242133	1276750	30-Jul-99	**active**	rooftop
I-90	WASHDOT I-90 Bridge	218357	1286598	Fall 1994	active	12.2
SR520	WASHDOT SR 520 Bridge	236899	1288697	Fall 1994	**active**	14.4
	NOAA ISIS at Sandpoint	251256	1291462	21-Mar-95	**active**	20
WBAN # 24234	Boeing Field	197997	1278128	1-Jan-30	**active**	6.1 (10/22/65-) 10.0 (12/9/1998-)
WBAN # 94248	Renton Municipal Airport	185459	1298492	1-Sep-61	active	8.8 (1/1/93-) 10.0 (10/8/1998-)

Northing/Easting in State Plane feet, Washington North, North American Datum 1983

†The Sea-Tac meteorological observation location has changed a number of times over the last 50+ years. This is the current location as of 2/4/2002. Sea-Tac was converted to the Automated Surface Observation System (ASOS) beginning on October 1, 1996.

The Boeing Field station was converted to ASOS beginning on December 9, 1998.

The Renton Municipal Airport station converted to ASOS beginning on October 8, 1998.

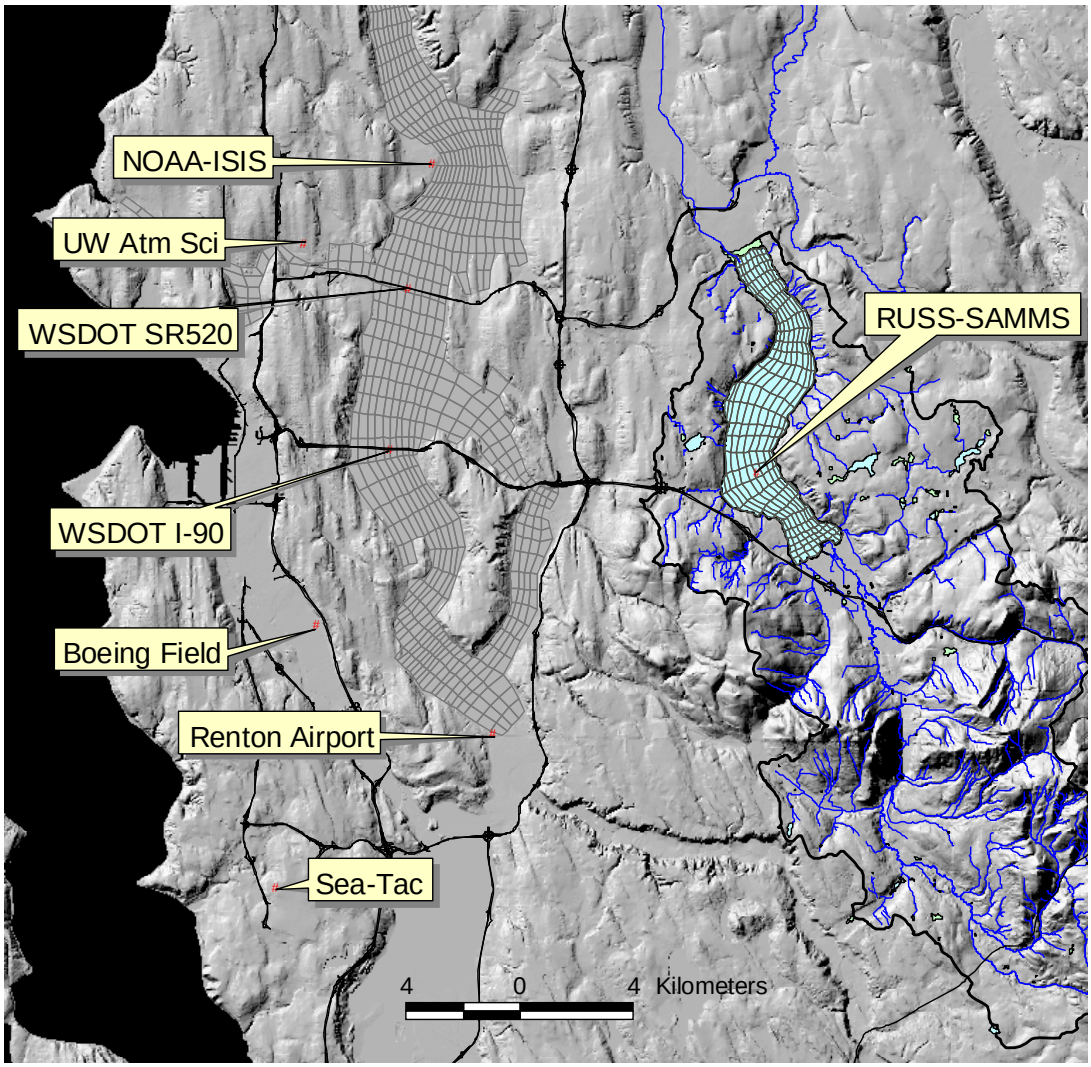


Figure 63 Selected meteorological stations in the vicinity of the Sammamish River.

A Remote Underwater Sampling Station (RUSS) buoy (SAMMS) equipped with a meteorological observation station was deployed on Lake Sammamish in July 2000. However, due to technical difficulties and vandalism, there are data gaps and some of the data are of questionable quality – particularly wind direction. When the meteorological data have been reviewed and suspect data identified and censored from the data set, these data may also be used to evaluate model performance. Currently, the RUSS buoy wind speed data have been used primarily to support the Wind Adjustment Factor used in the model calibration.

The Sea-Tac, UW, NOAA Sandpoint and SAMMS RUSS buoy data are described in more detail below.

4.4.1 Sea-Tac International Airport

Hourly records for air temperature, dew point, wind speed, wind direction, and cloud cover are available from the NOAA's National Climatic Data Center (NCDC) for Sea-Tac International Airport since 1948. The specific location and heights of the instruments above the ground have changed over time (Table 10).

Beginning in October 1996, the station was converted to the Automated Surface Observation System (ASOS). Some of the most relevant changes that occurred due to system automation were standardization of the anemometer height (10 m) and conversion from strip chart recording of wind and estimation of 10-minute average wind speeds by eye to computerized recording and averaging of wind data. Conversion to ASOS also eliminated the reporting of cloud cover in tenths of sky. ASOS also does not report cloud cover above 12,000 ft. Cloud cover is currently reported for one or more ceiling heights using text descriptions (e.g., CLR-clear, SCT-scattered, OVC-overcast) that translate into Octa ranges (eighths of sky).

Hourly Sea-Tac data supplied by EarthInfo, Inc. through 2003 on CD-ROM were extracted into TD1440 ASCII format and processed using a Fortran program developed to extract data to a comma-delimited file format suitable for importing into an electronic database. Hourly data were purchased from NCDC in DATSAV3 format and processed using a Fortran program to develop hourly cloud cover in tenths for model input for the post-ASOS period. Comparisons were made between pre- and post-ASOS sky cover summation codes[11] and reported cloud cover in tenths to derive conversions between the sky cover summation codes and cloud cover in tenths for the ASOS records (Table 11). Table 11 also presents the conversions used to develop the cloud cover inputs for the HSPF watershed models. Note that the values and the details of the two methods differ. An effort will be made to adopt a consistent method for both models in the future.

The hourly meteorological data used in the model and monthly averages for the period 1995-2003 are shown in Figure 64.

[11] The DATSAV3 code that denotes the portion of the total celestial dome covered by all layers of clouds and other obscuring phenomena at or below a given height.

Table 10. Station history for Sea-Tac International Airport meteorological observations.

Location	Occupied		Latitude North	Longitude West	Elevation Above (meters)						
					Sea Level	Ground					
	From	To			Ground Temperature	Wind Instrument	Extreme Temperature.	Psychrometer	Sunshine Switch	Weighing Rain Gauge	8 in Rain Gauge
Sea-Tac Airport	Apr. 2, 2002	Present	47°27’	122°19’	112.8	10.0	?	?	?	?	?
Sea-Tac Airport	Oct. 1, 1996 **j**	Apr. 2, 2002	47°28’	122°19’	121.9	10.0	?	?	?	?	?
Admin Bldg.	Dec. 11, 1959	Oct. 1, 1996	47°27’	122°18’	121.9	6.1	1.8 (23.5)	1.5 (23.5)	27.7 **%**	0.9 **f** (23.5 **g**)	0.9 (22.9)
Admin Bldg.	Nov. 1, 1956	Dec. 11, 1959	47°27’	122°18’	117.7	34.1 (6.1 **c**)	1.5 **b**	1.5 **b**	--	--	0.9
Admin Bldg.	Mar. 24, 1955	Nov. 1, 1956	47°27’	122°18’	114.6	33.2	1.5 **a**	1.5 **a**	--	--	0.9
Admin Bldg.	Nov. 17, 1949	Mar. 24, 1955	47°27’	122°18’	115.5	33.2	1.8	1.5	--	--	0.9
Control Tower	Nov. 21, 1944	Nov. 17, 1949	47°27’	122°18’	115.5	13.1	1.5	1.5	--	--	0.9

Source: 2002 Local Climatological Summary, National Climatic Data Center, Asheville, NC.

a Moved 1000 ft NNE of previous site.

b Moved 210 ft WSW of previous site.

c Moved to field site 11/21/1959.

d Standby equipment. Roof site effective 9/23/1967.

f Added 1/1/1965.

g Moved to roof site 2/1/1966

% Commissioned 10/7/1968

j Automated Surface Observation System (ASOS) commissioned 10/1/1996. Ground elevation 136.2 m.

Table 11. Cloud Cover code descriptions and translation from Octas to tenths.

Code	Description	Equivalent in Octas	CH3D Decimal Equivalent	HSPF Decimal Equivalent †
CLR	Clear	0/8	0.0	0.0
FEW	Few clouds	1/8 to 2/8	0.2	0.1875
SCT	Scattered clouds	3/8 to 4/8	0.28	0.4375
BKN	Broken clouds	5/8 to 7/8	0.79	0.75
OVC	Overcast	8/8	1.0	1.0
POB	Partly obscured	Not specified (used 8/8)	0.47	Not specified
OBS	Obscured	8/8	1.0	Not specified

† Details of the approach used to develop cloud cover inputs to the HSPF models is provided in (King County in progress)

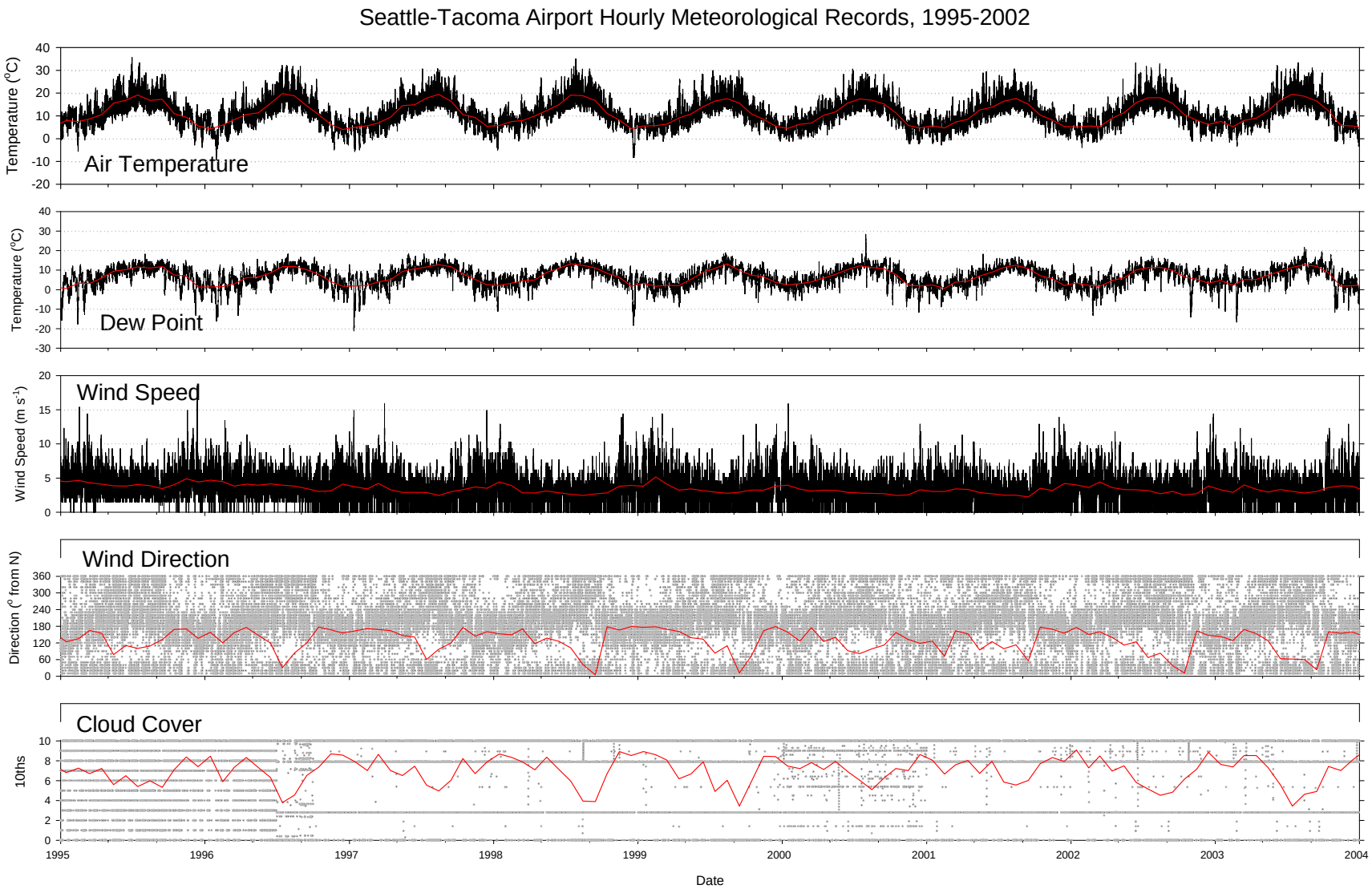


Figure 64 Hourly Sea-Tac meteorological data used in the Sammamish River model (red line is monthly average), 1995-2003.

4.4.2 NOAA Sandpoint Solar Radiation

As part of the Integrated Surface Irradiance Study (ISIS) conducted by NOAA (http://www.srrb.noaa.gov/isis/), solar radiation has been monitored since March 21, 1995. The annual hourly data in ASCII format were downloaded from their ftp site and compiled into a database. These data were reviewed and suspect data were identified. These data were supplemented with data collected at the University of Washington (see below) when available. Remaining data gaps were filled using the solar radiation computations in CE-QUAL-W2 (Cole and Wells 2003) and Sea-Tac cloud cover data in tenths. The hourly solar radiation data used in the model are presented in Figure 65.

4.4.3 University of Washington Atmospheric Sciences

The Atmospheric Sciences Department at the University of Washington has been collecting meteorological data for many years, but only data collected since July 1999 is readily accessible from their website (http://www-k12.atmos.washington.edu/k12/grayskies/nw_weather.html). The available 1-minute data were downloaded by year and compiled into a database. These data include air temperature, dew point, wind speed, wind direction, and solar radiation. The solar radiation data were processed into hourly average values and reviewed for use in the model. These data were used to supplement the solar radiation data collected at the NOAA Sandpoint facility (see Figure 65).

4.4.4 South Lake Sammamish RUSS Buoy

A meteorological station was installed as part of the RUSS buoy deployed in the southern basin of Lake Sammamish (SAMMS) in July 2000. The station is equipped with an R.M. Young™ weather station with sensors for air temperature-relative humidity, wind speed, wind direction (magnetic), and barometric pressure. The station is also equipped with a pyranometer (LiCor LI-200) that measures global solar radiation. The anemometer (wind speed and direction monitor) is approximately 2 m above the lake surface. Sampling frequency has varied from 6 minute to hourly intervals, but has been recording at 20-minute intervals since July 2003. There are a number of data gaps and some of the data are of suspect quality – primarily the initial air temperature and relative humidity measurements due to sensor failure and wind direction due to an act of vandalism in September 2001 that required the buoy to be rebuilt. Following reconstruction of the buoy, some difficulties were encountered in orienting the anemometer, which were compounded by a second act of vandalism a year later resulting in the alteration of the anemometer orientation. Data gaps have also occurred due to problems associated with the water column profiler, telecommunications, and power supply.

Figure 66 presents the available meteorological and solar radiation data collected from July 2000 through the end of 2003 along with annotations of significant problems associated with the data.

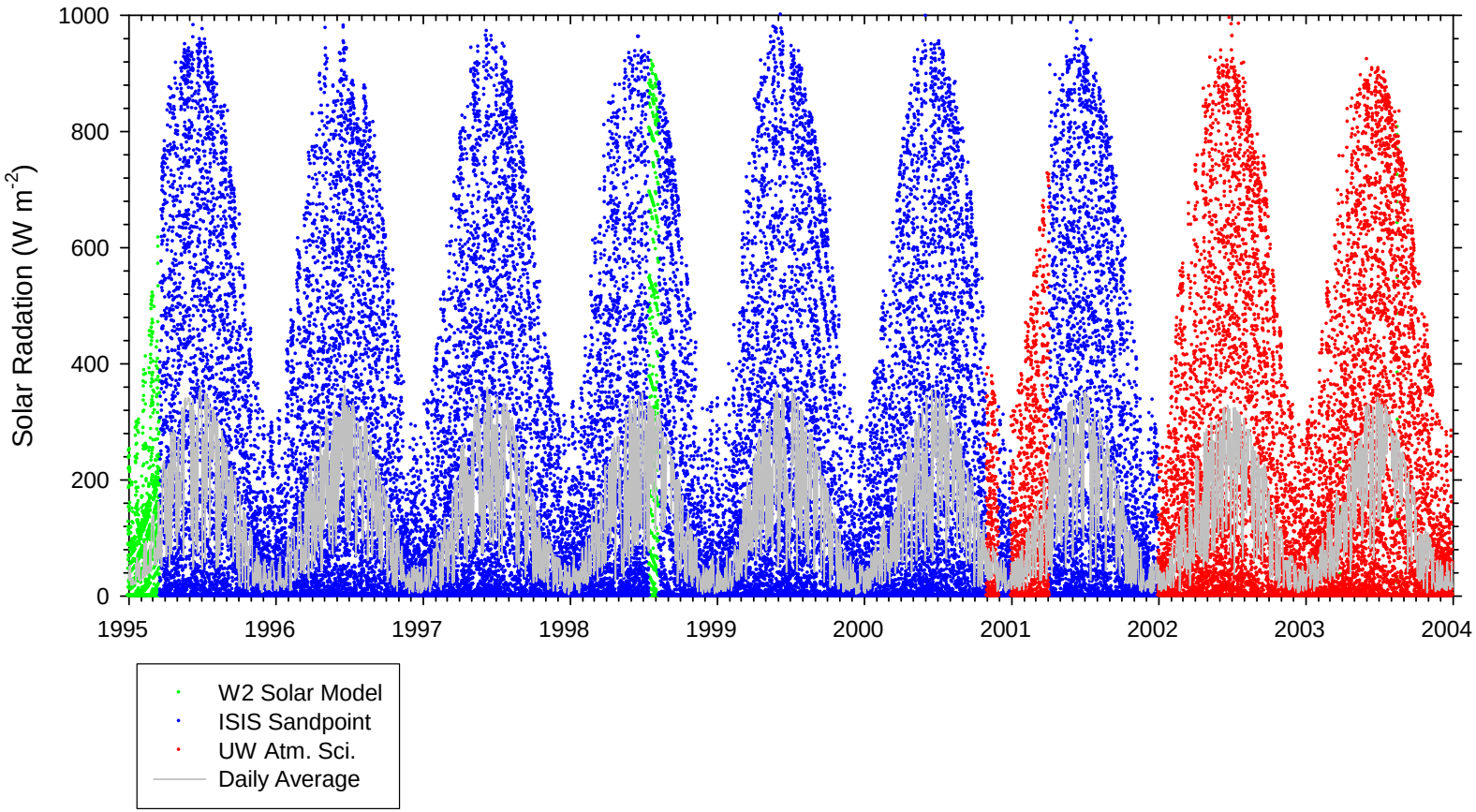


Figure 65 Solar Radiation data used in the Sammamish River model, 1995-2003.

[Note: Red dots = UW Atmos. Sci.; Blue dots = ISIS Sandpoint; Green dots = W2solar model]

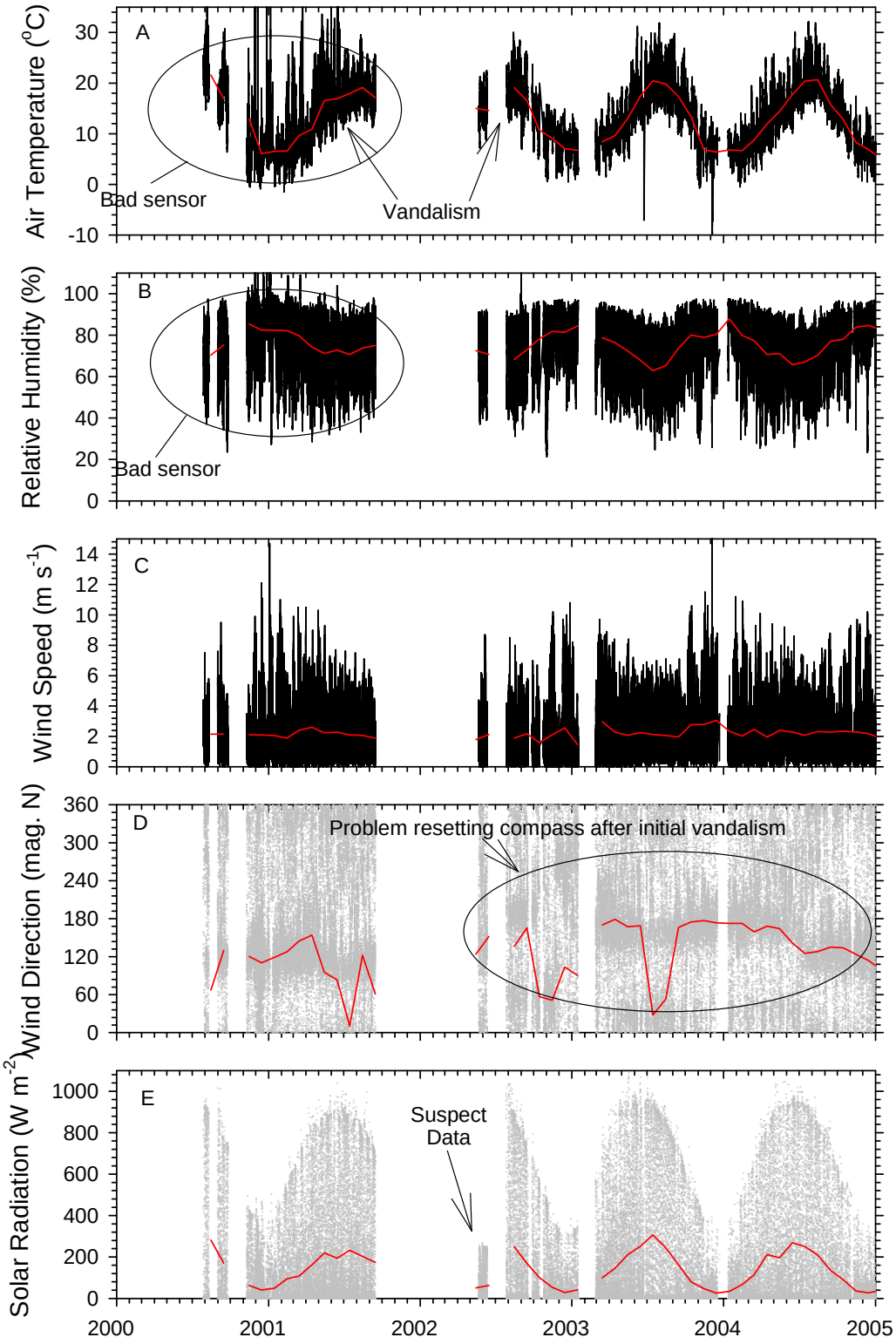


Figure 66 Meteorological and solar radiation data recorded by the SAMMS RUSS buoy, 2000-2004.

5.0. MODEL CALIBRATION

Initial calibration of the Sammamish River CE-QUAL-W2 Version 3.2 model has been achieved through several steps that occurred in approximately the following order.

1. Incorporation of the influence of dynamic shade using the available high resolution lidar to estimate the height of vegetation along the river. A detailed description of the methods used to develop the riparian and topographic shade inputs to the model can be found in King County (2005c).

2. The CE-QUAL-W2 FORTRAN code was modified to include the influence of submerged aquatic biomass on the resistance to flow along the channel. The need for this modification is described in more detail below.

3. Replaced the submerged aquatic plant light limitation function that included photo-inhibition with a simpler half-saturation relationship. The code modifications are described in more detail below.

4. Eliminated nutrient limitation of submerged aquatic biomass by setting the half-saturation constants for nitrogen and phosphorus to 0.000.

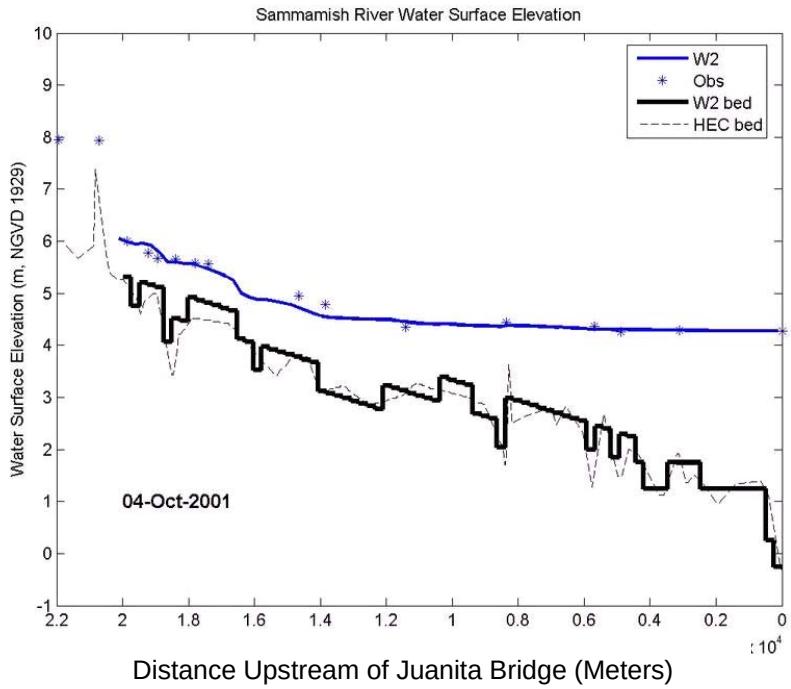
5. Switched from 0- to first-order sediment decay and reduced the sediment decay rate to 0.25 day^{-1}.

6. Trail-and-error adjustment of the parameters that affect submerged aquatic plant growth (primarily light half-saturation and maximum growth rate) and the parameters that affect the amount of bottom friction added by aquatic plant biomass.

7. Review of kinetic flux output to identify cause of elevated summer ammonia concentrations predicted by the model and make parameter adjustments to better fit model predictions to available observations. This was achieved by reducing the ammonium decay rate (NH4DK) from 0.12 to 0.06 day^{-1}.

After the model bathymetry was developed and the model input files set up, initial model runs indicated that the model became unstable during the late summer simulation period unless the Manning's bottom friction constant in the model was increased from 0.03 to 0.07. This increase allowed the model run to remain stable throughout the year but resulted in an over-prediction of winter water surface elevations (Figure 67). The timing of the need to increase the friction factor, the observation that the river contains a relatively dense cover of aquatic vegetation in summer, and the available literature indicating the influence of aquatic vegetation on river flow (Green 2005) suggested that river hydraulic behavior in summer was being influenced by aquatic vegetation.

Although version 3.2 of the model did not include the effect of aquatic plant biomass on bottom friction, version 3.2 of the model had been modified as part of a TMDL study of the Lost River between Oregon and California (Tetra Tech 2005). The modified code was obtained and



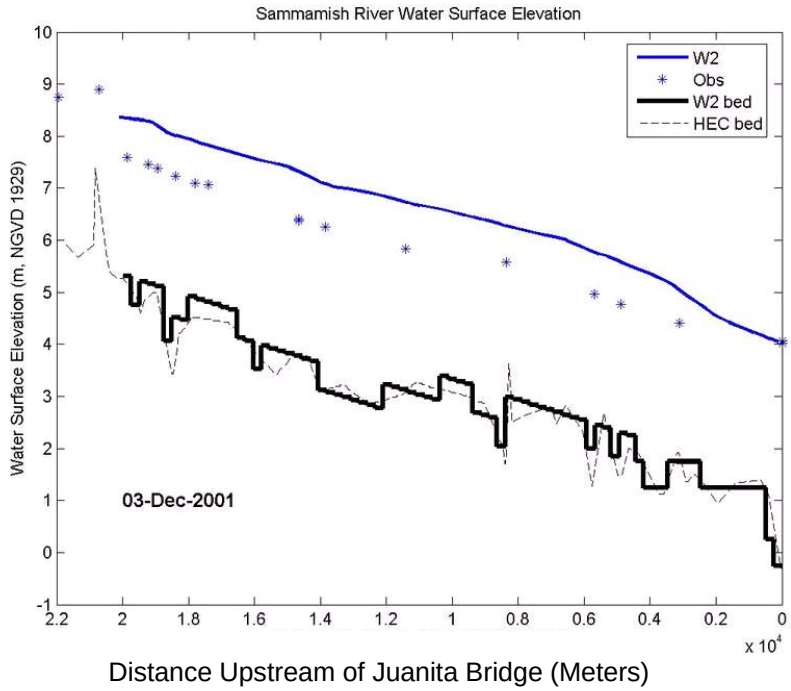


Figure 67 Example comparisons of model-predicted vs. observed water surface profiles with a constant Manning's n-value of 0.07. (top) Late summer – October 4, 2001 and (bottom) winter – December 3, 2001.

reviewed for potential incorporation into the Sammamish River CE-QUAL-W2 model. The selected approach was similar to the one developed for the Lost River TMDL model. The code was modified to make the Manning's friction value a function of aquatic plant biomass using a half-saturation formulation:

$$n = \min\left[n_{\max}\left(\frac{EPI}{EPI + Km} \right), 0.03 \right]$$

Where,

n = Manning's n (unitless)

EPI = Aquatic plant biomass in a particular model segment layer (g m^{-3})

K_m = Half-saturation concentration of aquatic plant biomass effect on n (g m^{-3})

n_{max} = Maximum friction factor (unitlesss)

and 0.03 is the minimum allowable friction factor. The effect of aquatic plant biomass on Manning's n for n_{max} = 0.1 and K_m = 50 is shown in Figure 68.

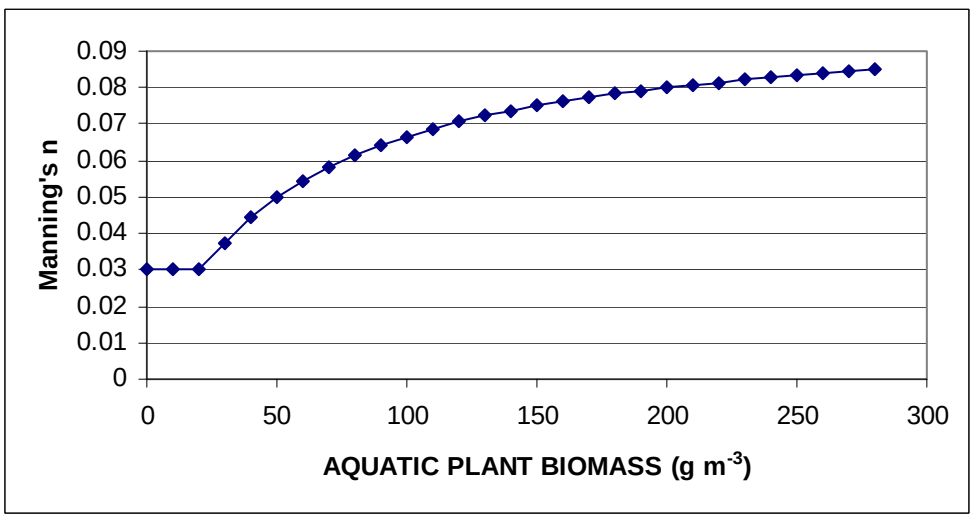


Figure 68 Example relationship between aquatic plant biomass and Manning's n based on n_{max} = 0.1 and K_m = 50 g m^{-3} using the half-saturation equation above.

In addition, the aquatic plant growth light-limitation function was changed from Steele's equation, which incorporates the effect of photo-inhibition to a simple half-saturation relationship more appropriate for rooted aquatic plants. The modified CE-QUAL-W2 version 3.2 FORTRAN code is available on request.

5.1 Model Control Flags and Coefficients

Selected model control and calibration parameters used in the current model are summarized in Appendix B. The reader is referred to the CE-QUAL-W2 Version 3.2 user's manual for detailed information about model formulations and parameters (Cole and Wells 2003). With the exception of the wind speed observation height parameter (WINDH), model flags and coefficients were not changed over the 1995-2003 simulation period. The wind speed observation height was set to 6.1 m for 1995- September 1996 and 10.0 m from October 1996-2003 to reflect the change in anemometer height due to the implementation of ASOS at Sea-Tac International Airport in October 1996. The dynamic topographic and riparian shade algorithms implemented in version 3.2 using the inputs derived from the high resolution LiDAR data (derived from flights conducted during leaf-off periods between November 2002 and December 2003). A wind adjustment coefficient of 1.0 (i.e., no adjustment of observed wind) was used in all years – the model temperature predictions were reasonably good without adjustment of this coefficient and minor adjustment of this coefficient could not be justified as a "tuning" parameter.

Observed solar radiation and the "Term-by-Term" heat exchange algorithm[12] that explicitly computes the various components of surface heat exchange (i.e., solar, incoming and outgoing longwave, evaporation, and conduction) were used in the model (Appendix Table 17). The upstream waterbody (WB1) was modeled as a riverine section using the Nickuradse (NICK) mixing length and vertical eddy viscosity formulation and the downstream waterbody (WB2) was modeled as a lake section using the W2N vertical eddy viscosity formulation (Cole and Wells 2003, p. A-66). An implicit treatment of vertical eddy viscosity in the longitudinal momentum equation was used to allow longer time steps and the maximum vertical eddy viscosity was set to 2 m^2 sec^{-1} (Appendix Table 17). Model default values were used to simulate the effects of water and particles (organic and inorganic) on the depth of light and heat into the water column (Appendix Table 18).

The generic constituent variables in CE-QUAL-W2 were used to simulate a conservative tracer, copper, fecal coliform bacteria and *E. coli* (Appendix Table 19). The inorganic suspended solids partition coefficient used to simulate the partitioning of copper to solids (K_d = 1000 L kg^{-1}, log K_d = 5.0) was derived from published studies (Allison and Allison 2005). The die-off and settling rates for fecal coliform and *E. coli* were first approximations used to evaluate initial model performance.

The model default value of 1 m day^{-1} was used as the settling velocity of the single class of suspended particles considered in the current model (Appendix Table 20). The algorithm that incorporates sediment resuspension in the model was not activated in this application.

[12] Term-by-Term heat exchange algorithm refers to the use of equations that attempt to account for each heat exchange component between the atmosphere and surface water explicitly as opposed to the Equilibrium Temperature approach, which relies on a simplified approach to estimating the net balance of the surface water heat exchange terms.

Algal flags and coefficients were set in an attempt to create three ecologically distinct groups (Appendix Table 21):

- Diatoms adapted to cooler temperature ranges with a low light saturation constant and relatively high growth and settling rates. Diatoms also contain and require silica for growth.
- Green algae adapted to moderate temperature ranges with moderate light saturation constant and growth and settling rates.
- Cyanobacteria (blue-green algae) adapted to moderate to very warm temperature ranges with high light saturation constant and low growth and settling rates.

In order to simulate the growth of the single class of rooted aquatic macrophytes considered in the model, epiphyton half-saturation values were set to zero to remove any potential nutrient limitation of growth (Appendix Table 22). A value of 10 g m^{-3} for the plant biomass half-saturation effect on Manning's friction value (EPI_HCC) was found to give a reliable increase in bottom friction during the aquatic plant growth period, which resulted in an acceptable match between observed and modeled water surface profiles.

Default values were used for organic matter and nutrient flags and coefficients (Appendix Table 23 and Appendix Table 24.

As might be expected, sediment control flags and coefficients had a significant effect on simulated water column nutrient, DO and pH levels. Final flags and parameter values are shown in Appendix Table 25.

A variety of reaeration formulations for streams, rivers and lakes are available in the model. Currently, reaeration in the upstream waterbody (WB1) is computed using the Melching and Flores (1999) formula appropriate for controlled channels (Appendix Table 26). Reaeration in the lower waterbody (WB1) is computed using the default formulation described on page B-34 of Cole and Wells (2003).

5.2 Water Surface Elevations

Generally, the model as currently configured and calibrated reproduces the observed water surface elevations reasonably well (average absolute mean error less than 10 cm), particularly during the summer when aquatic plants contribute to higher water surface elevations than would be expected in the absence of plant growth. Comparisons of observed water surface profiles to model predictions are shown in Figure 69 through Figure 75.

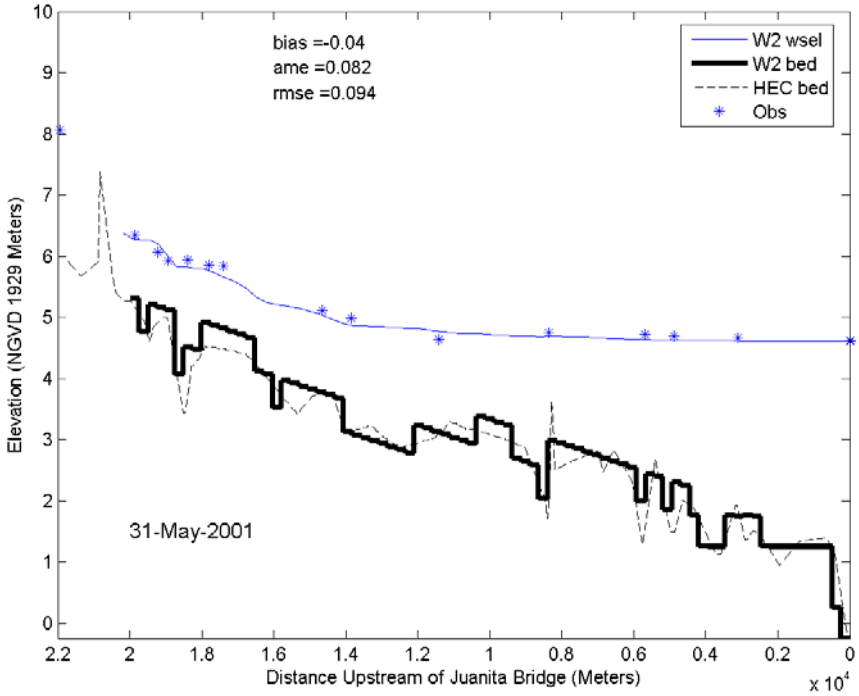


Figure 69 Comparison of observed and modeled water surface profile using model bottom friction based on aquatic plant biomass, May 31, 2001.

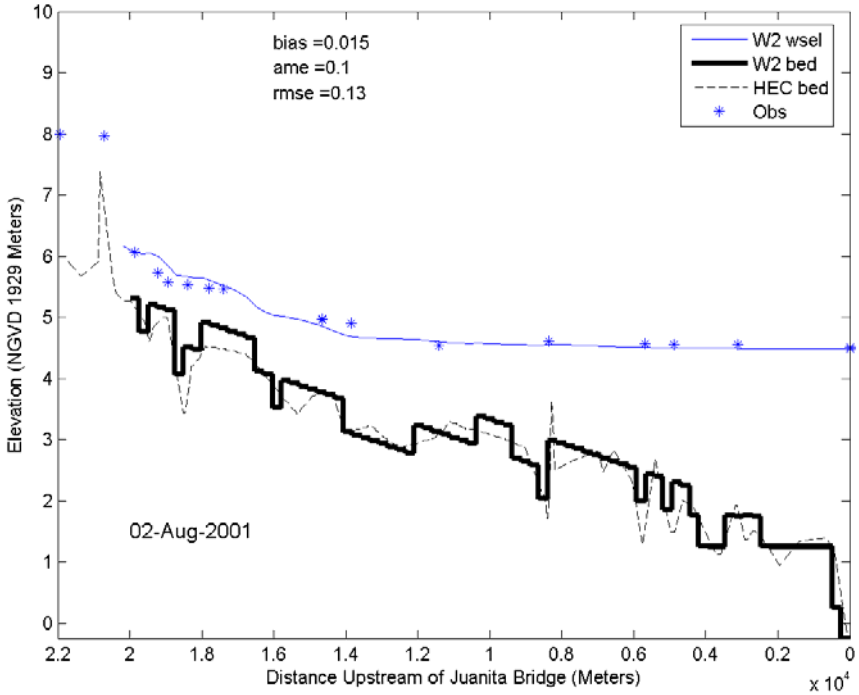


Figure 70 Comparison of observed and modeled water surface profile using model bottom friction based on aquatic plant biomass, August 2, 2001.

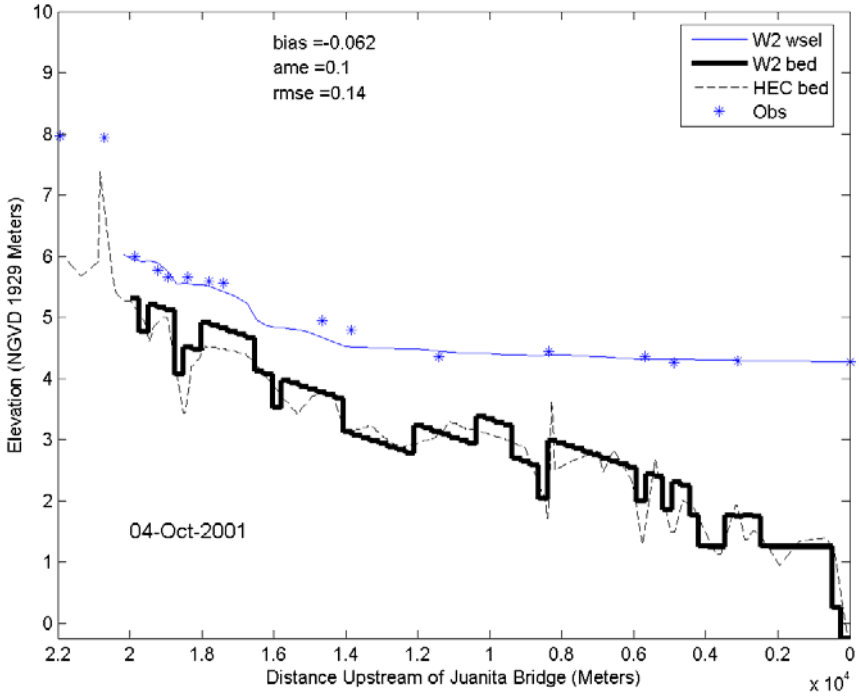


Figure 71 Comparison of observed and modeled water surface profile using model bottom friction based on aquatic plant biomass, October 4, 2001.

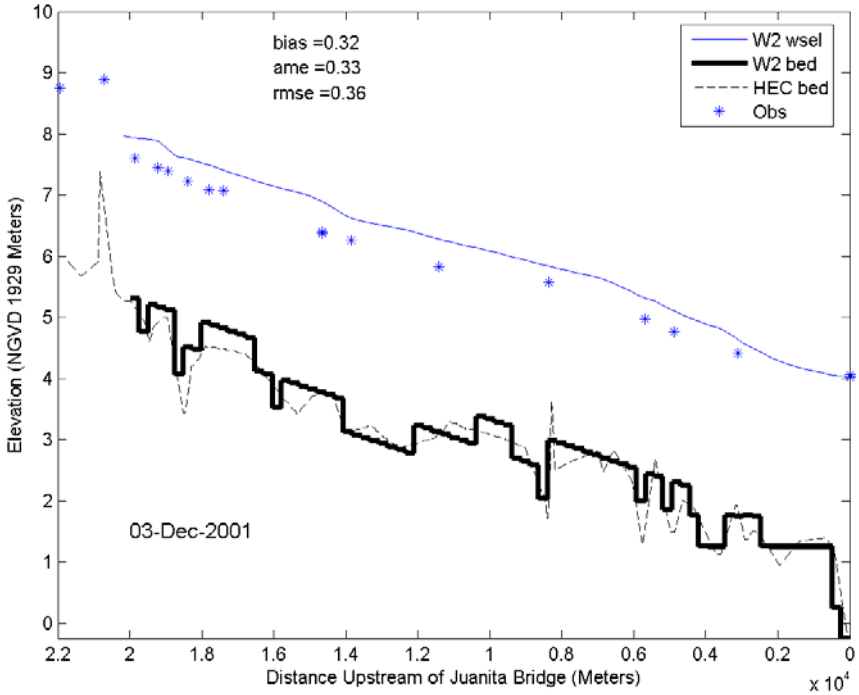


Figure 72 Comparison of observed and modeled water surface profile using model bottom friction based on aquatic plant biomass, December 3, 2001.

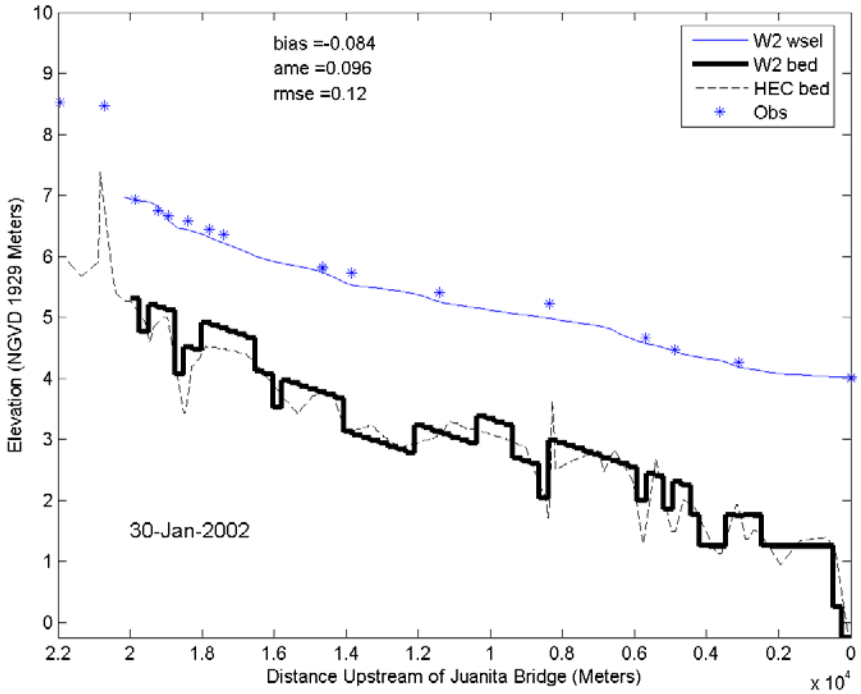


Figure 73 Comparison of observed and modeled water surface profile using model bottom friction based on aquatic plant biomass, January 30, 2002.

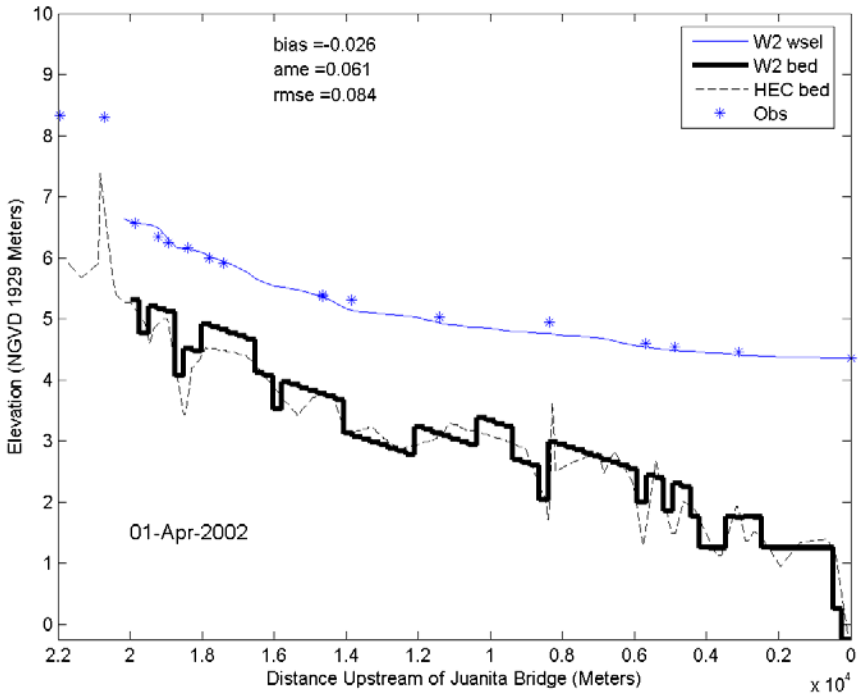


Figure 74 Comparison of observed and modeled water surface profile using model bottom friction based on aquatic plant biomass, April 1, 2002.

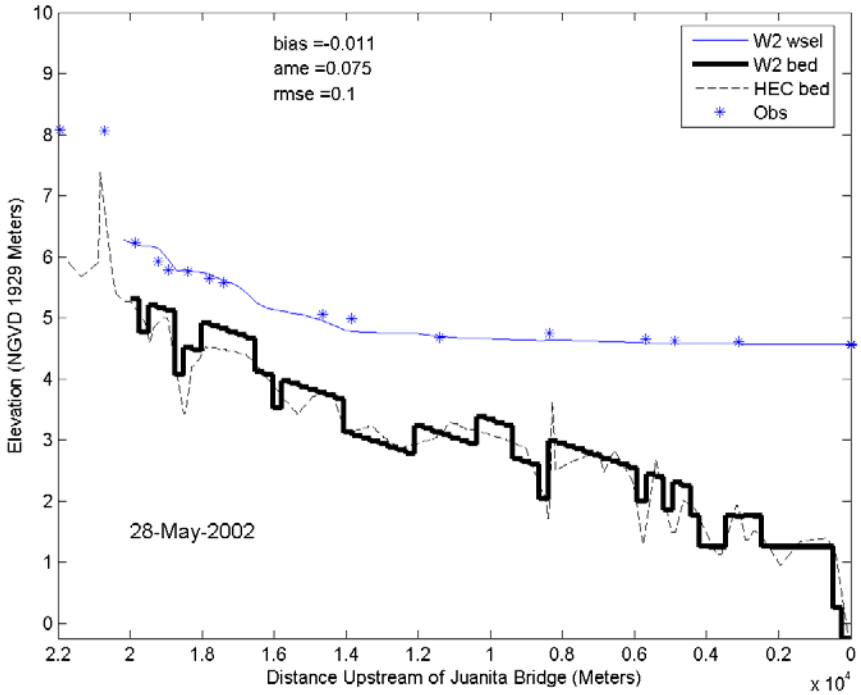


Figure 75 Comparison of observed and modeled water surface profile using model bottom friction based on aquatic plant biomass, May 28, 2002.

5.3 Temperature

The overall performance of the temperature model was reasonably good when compared to the available hourly temperature data (n = 155,182). The overall coefficient of determination (r^2) was 0.9874, which places the current model in the upper 90th percentile of mechanistic biogeochemical model performance for temperature prediction surveyed by Arhonditsis et al. (2004). The REM of 3 percent placed the model in the lower 20th percentile (lower REM indicates better model performance) based on the same survey (Arhonditsis et al. 2004).

Annual and overall error statistics of model temperature predictions are presented in Table 12. In general, there appears to be some seasonality to the errors – positive bias in summer and negative bias in winter (Figure 76). Comparison plots of modeled vs. observed hourly temperature data are available from the author upon request. Example plots of modeled vs. observed hourly temperatures for 1999 are presented in Figure 77.

Table 12. Summary of temperature prediction error statistics.

Year	BIAS (ME)	AME	RMSE	SE	REM
1999	-0.33	0.62	0.75	0.67	4.1%
2000	-0.14	0.62	0.78	0.76	4.4%
2001	-0.32	0.72	0.85	0.78	5.7%
2002	-0.48	0.70	0.86	0.71	5.7%
2003	-0.43	0.71	0.90	0.79	5.6%
Overall	-0.38	0.68	0.83	0.74	3%

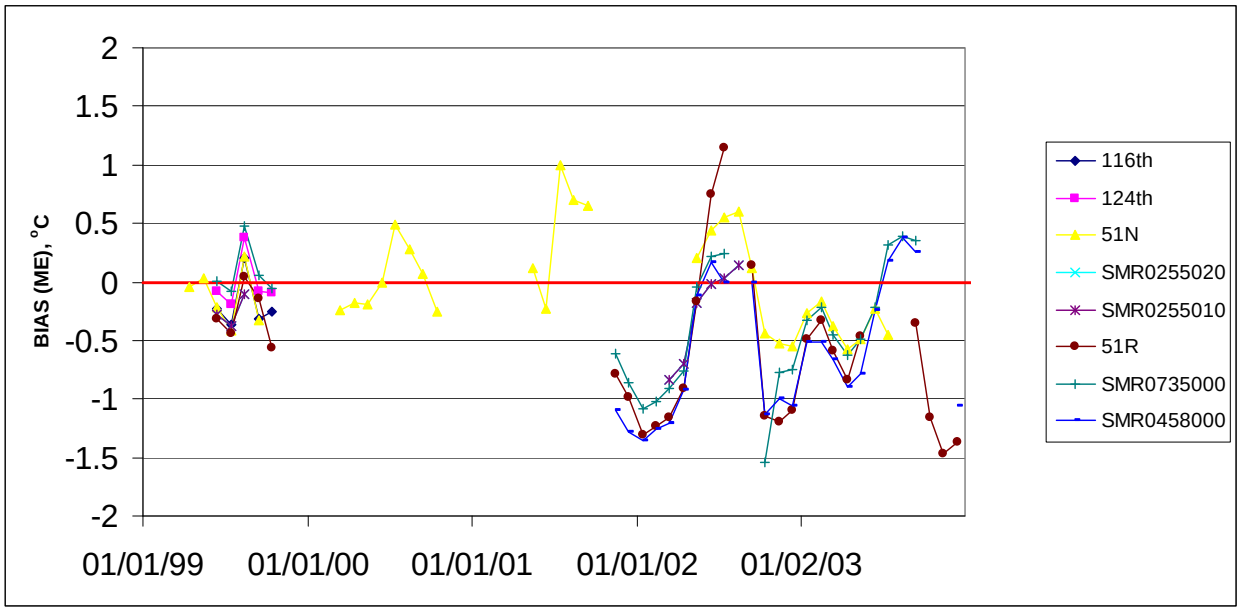


Figure 76 Monthly mean bias of predicted hourly temperatures, Sammamish River 1999-2003.

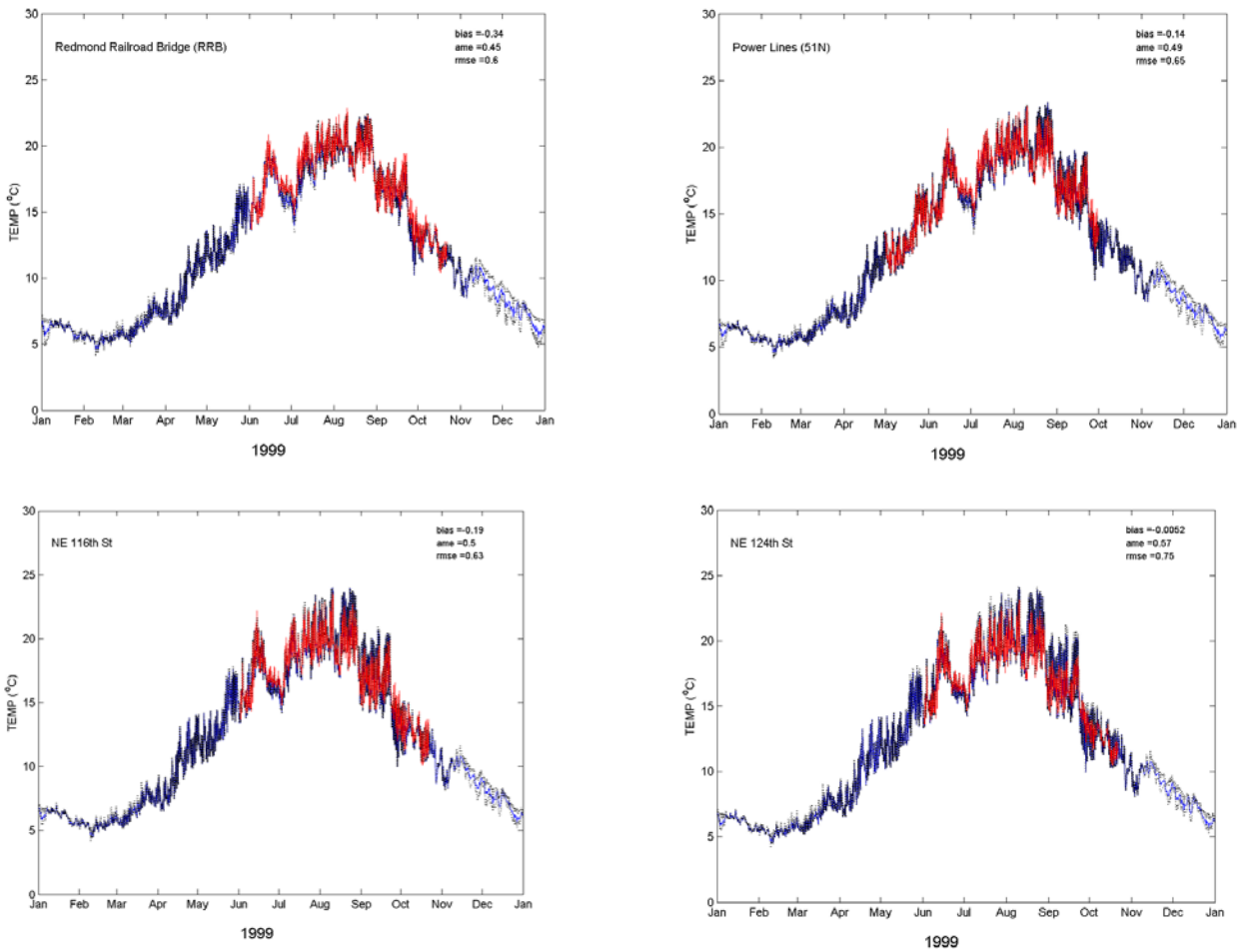


Figure 77 Plots of 1999 modeled (red lines) vs observed (blue lines) hourly temperatures.

Comparison of the 1999 summer FLIR data to predictions from the current and previous versions of the model are shown in Figure 78. All versions of the model have captured the general longitudinal changes in temperature from Lake Sammamish to below the confluence with North Creek near Bothell. However, the original version developed by JEEAI and the current version fail to predict the increase in surface water temperatures below North Creek as the river deepens and slows as a result of the backwater effect of Lake Washington. The 2002 version of the model adopted a 2 waterbody grid similar to the one used in the current version of the model to allow the model to better simulate surface warming in the lower river (King County 2002, Appendix B). It is unclear why the current version of the model does not reproduce the warming in the lower river reach. Further testing is recommended to identify and correct this problem.

Because the initial focus of the model was on summer temperatures, previous versions of the model were not compared to the 2000 winter FLIR data. Comparison of model predictions to the winter FLIR data, indicate that the model does capture the general magnitude and longitudinal variation in river surface temperatures. Further model testing should include an evaluation of the ability of the model to predict winter temperatures.

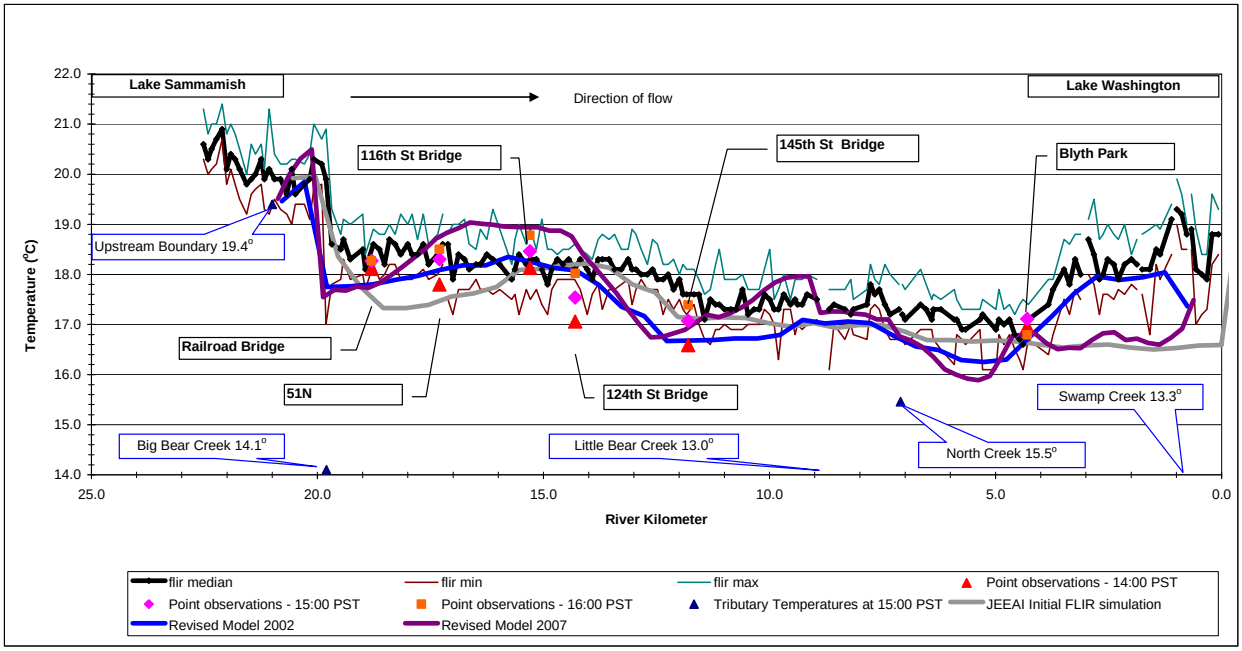


Figure 78 Comparison of modeled and observed river surface temperatures derived from the September 2, 1999 FLIR data.

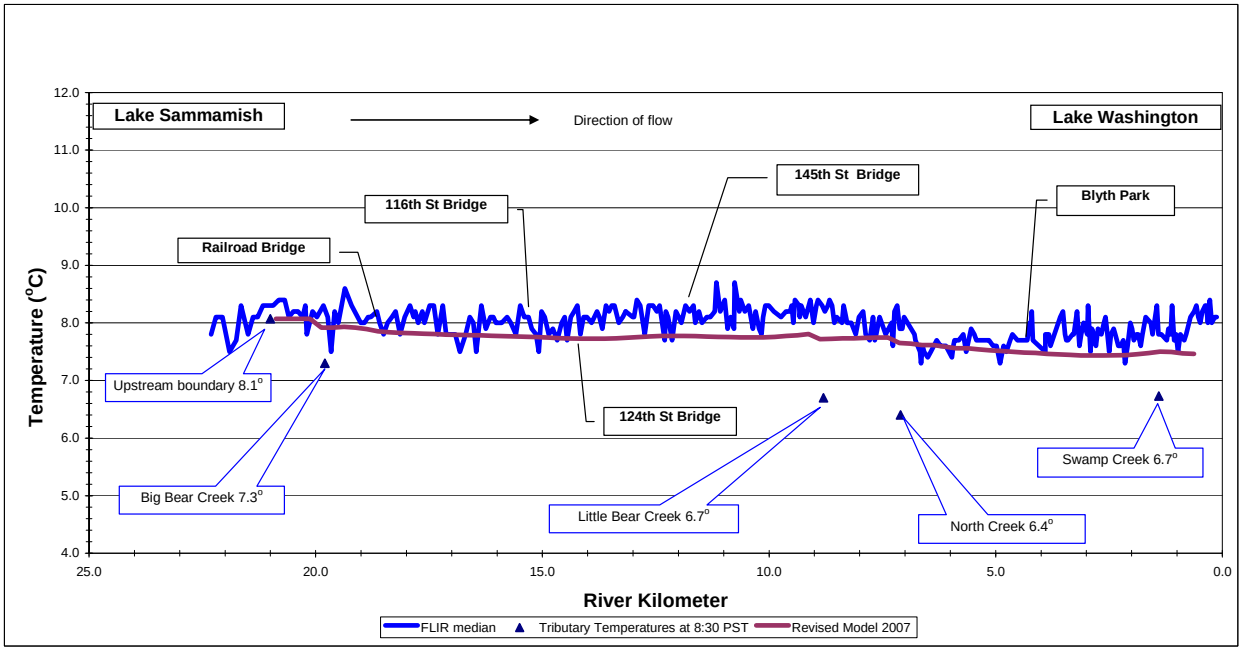


Figure 79 Comparison of modeled and observed river surface temperatures derived from the March 23, 2000 FLIR data.

5.4 Water Quality

Due to the large amounts and complexity of the available data used to test the water quality components of the current model, plots comparing observed and modeled water quality constituents for individual years and constituents will be provided by the author upon request. A Microsoft Access database containing all paired data and error statistics will also be provided. This will allow others to independently evaluate the model's capabilities with respect to time and space. A summary of the current model's performance along with summary statistics in graphical and tabular form follows.

A summary of model-prediction error statistics based on routine grab sampling data collected between 2000 and 2003 is provided in Table 13 and modeled vs. predicted linear regression results are provided in Table 14. The model prediction error statistics for temperature, DO, nitrate, ammonium, phosphate, silica and bacteria shown in Table 13 and Table 14 can be compared with the performance of published mechanistic biogeochemical model studies reviewed by Arhonditsis and Brett (2004) (Table 15). Relative to other published model error statistics (Table 15), the current Sammamish River W2 model performs best for predicting grab temperature data – similar to the errors observed for the continuous temperature data (see previous section). However, for other parameters (dissolved oxygen, nutrients, copper, phytoplankton biomass, and indicator bacteria) the current Sammamish River W2 model does not perform well relative to other published models suggesting that further work (data collection and/or model development/calibration) is needed to improve the ability of the model to predict these constituents.

To provide a sense of seasonal and interannual model prediction errors, plots of bias calculated from modeled and observed routine monitoring data are presented in Figure 80 through Figure 83. Since the available copper data were rather limited, annual average bias calculated from grab samples collected in September-October 2001 to 2003 are shown for dissolved and total copper in Figure 84. In general, the model has a tendency to significantly (REM>15%) over-predict DO, dissolved phosphorus and nitrogen compounds, and dissolved and total copper, and significantly under-predict chlorophyll *a*, TSS, and indicator bacteria concentrations. Based on visual inspection of Figure 80 through Figure 83, it appears that seasonal variation in model prediction bias occurs for DO and ammonia nitrogen. There is also a consistent positive bias in the prediction of total and dissolved copper (Figure 84).

Monthly average model bias for the continuous temperature, conductance, DO, DO saturation, and pH for May-October of 2003 is shown in Figure 85. Model-prediction error statistics based on the 2003 continuous data are provided in Table 16. These comparisons confirm the ability of the model to predict temperature (bias typically less than 0.5 ^{o}C and REM 3.4 percent), but highlight the previously noted positive bias for DO (REM 21 percent).

Table 13. Summary of model prediction error statistics for routine grab sample data, 2000-2003.

Parameter	n	BIAS (ME)	AME	RMSE	SE	REM
Temperature	160	-0.34	0.67	0.83	0.75	5.4
Alkalinity	139	-3.88	4.06	5.58	4.01	7.7
Conductance (as TDS)	158	-3.63	6.03	8.28	7.44	8.2
Dissolved Oxygen	154	1.14	1.54	2.05	1.70	16.4
pH	160	0.21	0.27	0.34	0.27	3.8
Total Phosphorus	139	-0.02	0.02	0.02	0.02	37.3
Soluble Reactive P	139	0.0002	0.003	0.005	0.005	25.3
Total Nitrogen	139	0.06	0.09	0.13	0.11	14.3
Ammonium-N	139	0.02	0.02	0.03	0.03	66.2
Nitrate-N	139	0.03	0.06	0.09	0.08	16.8
Dissolved Si	79	-0.001	0.46	0.63	0.63	8.1
Chlorophyll *a*	63	-3.61	3.61	4.31	2.35	99.7
Dissolved Organic Carbon	87	0.05	0.46	0.60	0.60	8.9
Total Organic Carbon	87	0.24	0.68	0.89	0.86	11.4
Total Suspended Solids	139	-2.26	3.00	8.57	8.27	61.2
Dissolved Copper	25	0.61	0.61	0.64	0.21	107.2
Total Copper	25	0.54	0.54	0.57	0.18	84.9
Fecal coliform	138	-20.52	64.84	160.18	158.86	62.1
E. coli	138	-32.42	58.15	109.57	104.66	59.2

n = Number of samples; ME = mean error; AME = absolute mean error; RMSE = root mean square error; SE = standard error; REM = relative error of the mean

Table 14. Summary of modeled vs predicted linear regression results for routine grab sample data, 2000-2003.

Parameter	n	Y-Intercept	Slope	r^2	*p*	
Temperature	160	1.2	0.93	0.9851	0.0000	**
Alkalinity	139	-11	1.30	0.8646	2E-61	**
Conductance (as TDS)	158	-11.0	1.21	0.6712	0.0000	**
Dissolved Oxygen	154	3.6	0.55	0.1511	0.0000	**
pH	160	3.2	0.53	0.1736	0.0000	**
Total Phosphorus	139	0.0	1.79	0.4655	0.0000	**
Soluble Reactive P	139	0.0	0.66	0.4546	0.0000	**
Total Nitrogen	139	0.1	0.80	0.6138	0.0000	**
Ammonium-N	139	0.0	0.38	0.5557	0.0000	**
Nitrate-N	139	0.0	0.82	0.6857	0.0000	**
Dissolved Si	79	-0.3	1.05	0.8278	0.0000	**
Chlorophyll *a*	63	3.3	31.42	0.0096	0.44	ns
Dissolved Organic Carbon	87	1.3	0.75	0.5862	0.0000	**
Total Organic Carbon	87	1.3	0.74	0.4460	0.0000	**
Total Suspended Solids	139	2.4	0.93	0.0187	0.11	ns
Dissolved Copper	25	0.27	0.25	0.1244	0.08	ns
Total Copper	25	0.4	0.22	0.2575	0.010	*
Fecal coliform	138	54.7	0.59	0.0864	0.0005	**
E. coli	138	56.6	0.63	0.1454	0.0000	**

** = significant at $p<0.005$; * = significant at $p<0.05$; ns = not significant ($p>0.05$); r^2 = regression coefficient; *p* = significance level

Table 15. Performance of mechanistic biogeochemical models (1990-2004) summarized by Arhonditsis and Brett (2004).

Regression Coefficient (r^2)

Percentile	T	DO	NO_3	NH_4	SRP	SiO_2	Phyto-plankton	Zoo-plankton	Bacteria
100th	0.99	1.00	1.00	0.99	0.96	0.98	0.98	1.00	0.64
90th	**0.98**	0.92	0.95	0.89	0.86	0.89	0.83	0.97	0.39
80th	0.97	0.88	0.91	0.78	0.8	**0.8**	0.76	0.9	0.24
70th	0.96	0.86	0.84	0.57	0.69	0.69	0.63	0.69	0.21
60th	0.95	0.78	0.79	**0.44**	0.57	0.66	0.56	0.37	0.18
50th	0.93	0.7	**0.68**	0.39	0.47	0.61	0.48	0.24	**0.06**
40th	0.92	0.62	0.56	0.29	**0.3**	0.52	0.41	0.19	0.03
30th	0.81	0.58	0.47	0.18	0.2	0.46	0.3	0.12	0.01
20th	0.62	0.52	0.37	0.13	0.13	0.35	0.16	0.09	0
10th	0.42	0.34	0.1	0.05	0.07	0.2	0.08	0.06	0

Bold values/shaded cells indicate that current model r^2 exceeds the performance of X percent (percentile value in the left column) of models evaluated by Arhonditsis and Brett (2004).

Percent Relative Error of the Mean (REM)

Percentile	T	DO	NO_3	NH_4	SRP	SiO_2	Phyto-plankton	Zoo-plankton	Bacteria
90th	2%	4%	**8%**	18%	**19%**	**18%**	20%	17%	21%
80th	4%	7%	18%	30%	26%	30%	26%	31%	25%
70th	5%	8%	26%	34%	32%	32%	32%	44%	33%
60th	**5%**	10%	32%	40%	36%	34%	37%	52%	35%
50th	7%	12%	36%	48%	42%	37%	44%	70%	36%
40th	7%	**14%**	44%	55%	47%	41%	51%	79%	37%
30th	9%	17%	57%	**65%**	55%	46%	58%	115%	42%
20th	11%	19%	68%	77%	69%	55%	66%	138%	49%
10th	15%	22%	88%	101%	84%	64%	79%	201%	59%
0th	25%	31%	554%	206%	218%	302%	**128%**	435%	**66%**

Bold values/shaded cells indicate that current model REM exceeds the performance of X percent (percentile value in the left column) of models evaluated by Arhonditsis and Brett (2004).

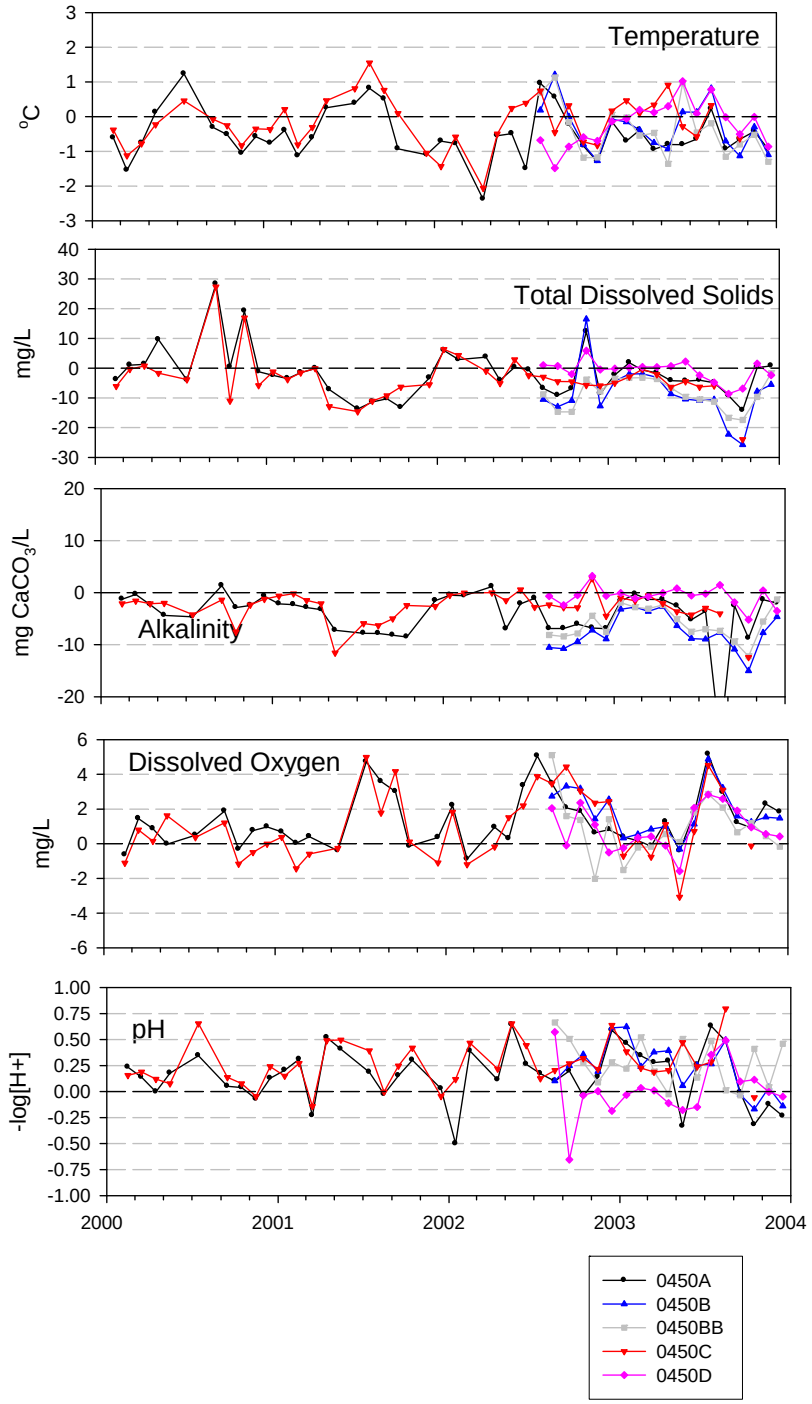


Figure 80 Model bias calculated from modeled and observed routine monitoring grab samples of temperature, conductance (modeled as TDS), alkalinity, DO, and pH, 2000-2003.

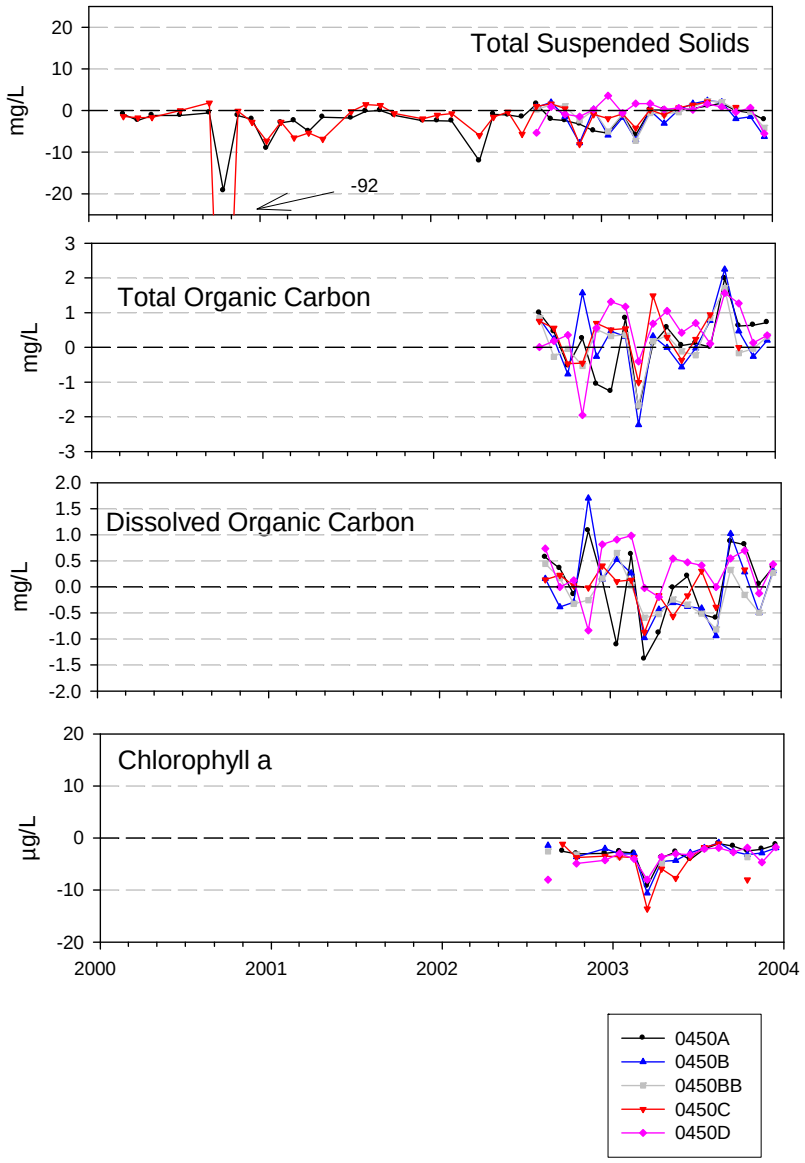


Figure 81 Model bias calculated from modeled and observed routine grab samples of TSS, TOC, DOC and chlorophyll *a*, 2000-2003.

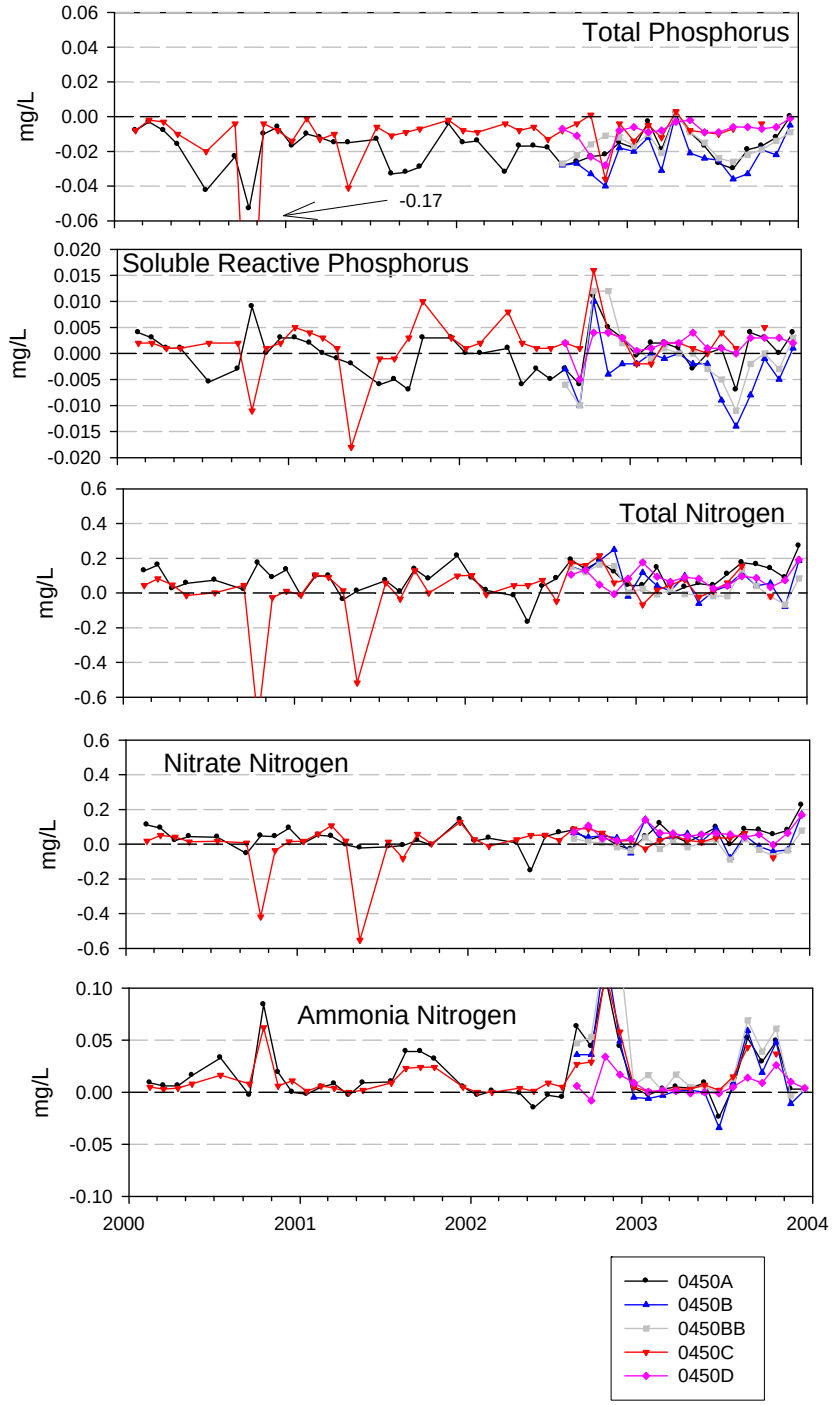


Figure 82 Model bias calculated from modeled and observed routine grab samples for TP, SRP, TN, NO_3-N and NH_3-N, 2000-2003

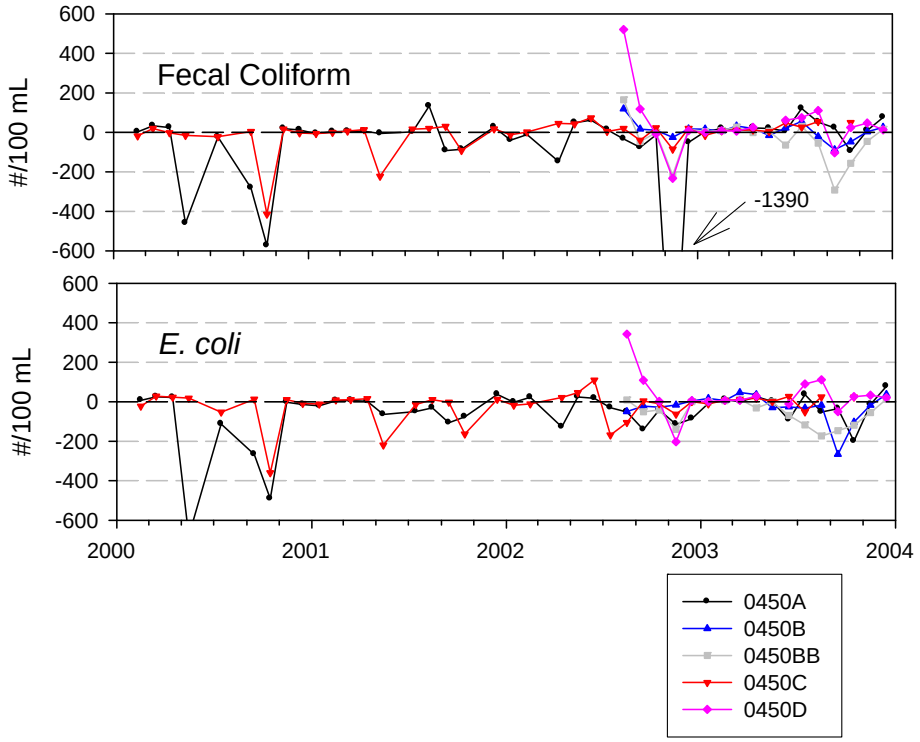


Figure 83 Model bias calculated from modeled and observed routine grab samples for fecal coliform and *E. coli* indicator bacteria, 2000-2003.

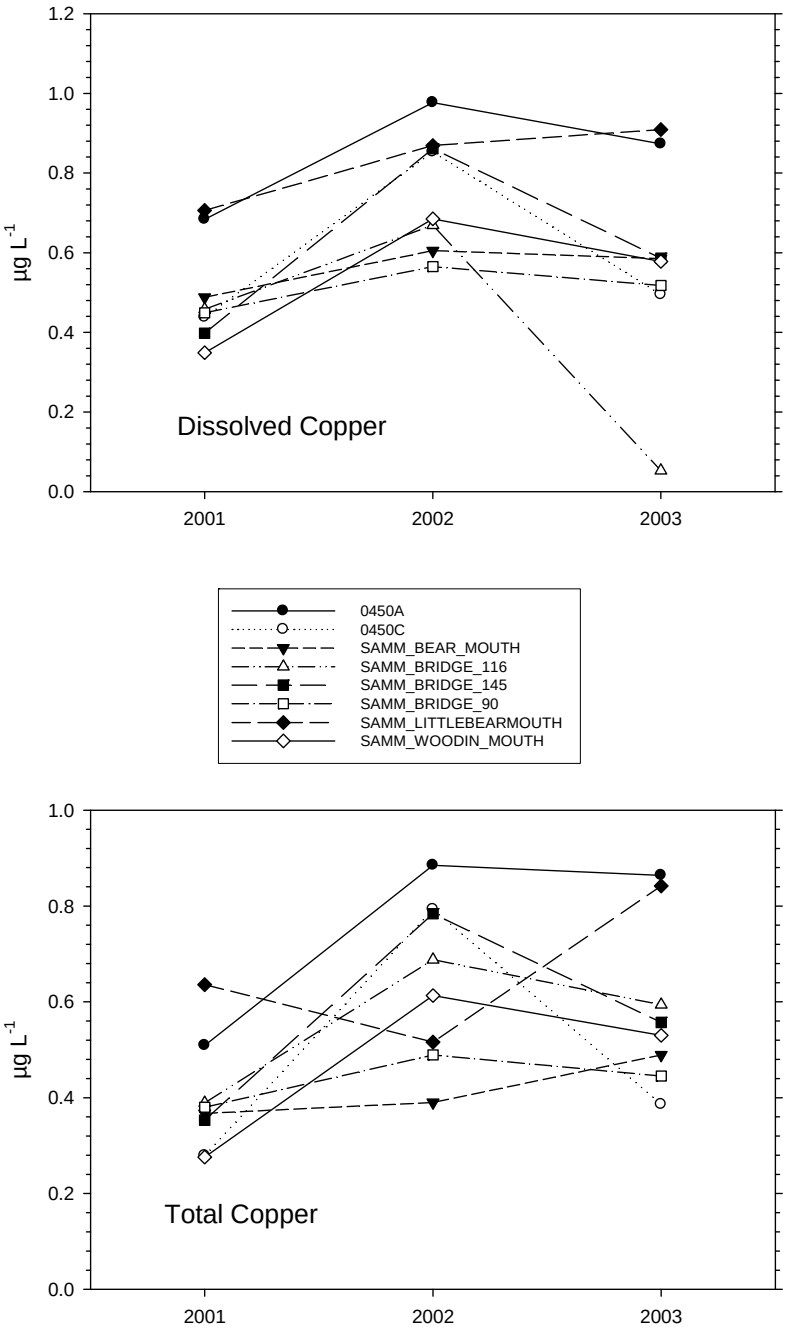


Figure 84 Annual (Sep-Oct) average bias calculated from modeled and observed routine grab samples for dissolved and total copper, 2001-2003.

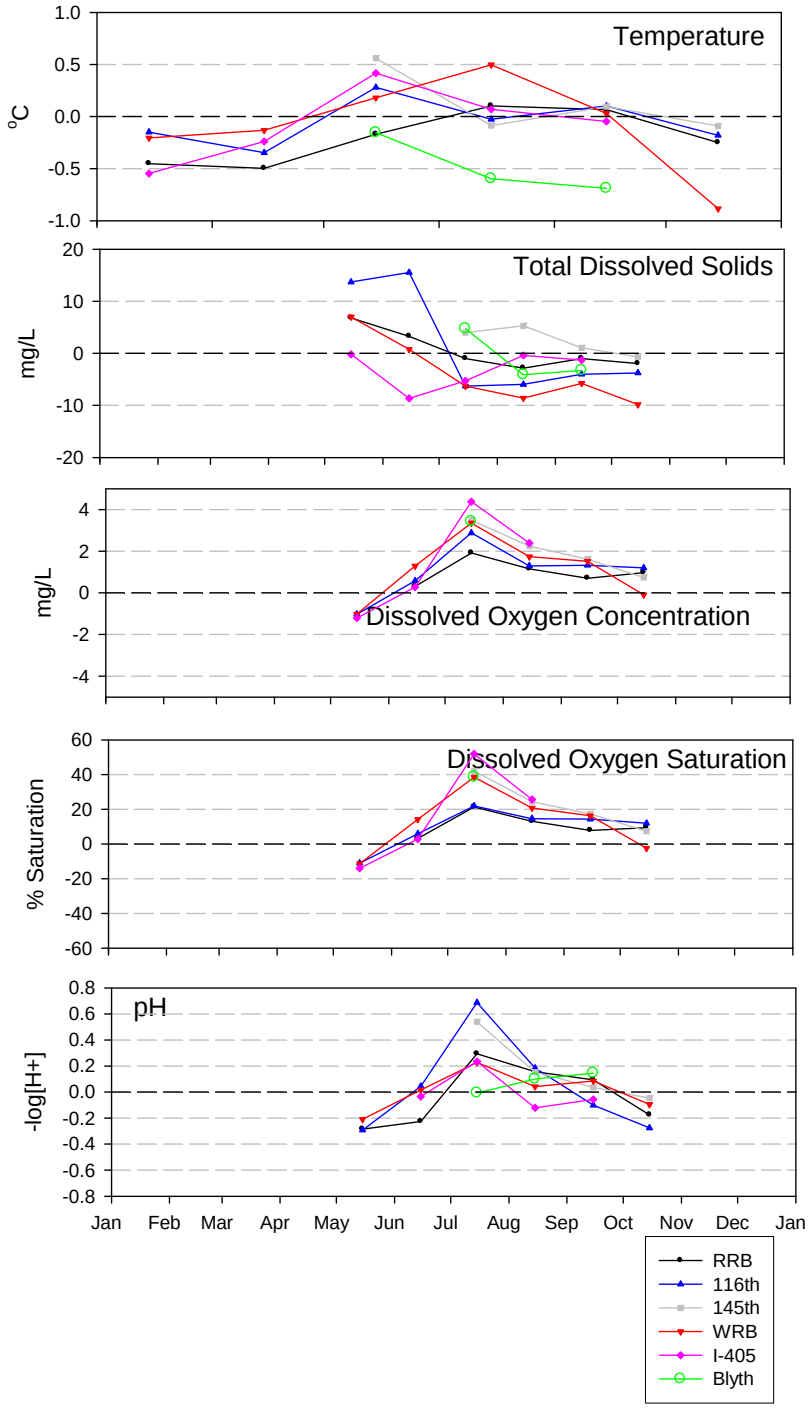


Figure 85 Monthly average model bias calculated from modeled and observed continuous (hourly) temperature, conductance (modeled as TDS), DO, DO saturation and pH, May-October 2003.

Table 16. Summary of model prediction error statistics for continuous temperature, conductance (modeled as TDS), DO, DO saturation, and pH, May-October 2003.

Parameter	n	ME	AME	RMSE	SE	REM
Temperature	7852	0.0	0.7	0.8	0.8	3.4
Conductance (as TDS)	7534	-2.5	5.2	6.4	5.9	6.8
Dissolved Oxygen	7081	1.6	1.9	2.3	1.6	21
DO percent saturation	7071	18	21	26	19	22
pH	7664	0.1	0.2	0.3	0.3	3.0

6.0. CONCLUSIONS AND RECOMMENDATIONS

A great deal of progress has been made in the development of a mechanistic water quality model of the Sammamish River. Based on comparisons to available data, the model is most capable of simulating water temperatures, except in the lower portion of the river influenced by the backwater from Lake Washington. The model as currently configured is a suitable tool for evaluating potential influences of riparian shade, groundwater flow restoration/augmentation, and other potential water temperature management actions proposed to improve the temperature conditions for salmon migrating through the river to their spawning grounds.

Primarily due to the difficulty of capturing the dynamics of aquatic plant growth in the river, the model does not perform as well for other water quality constituents of interest – particularly DO. The model also does not simulate total and dissolved copper well when compared to the limited amount of data currently available. The poor performance of the model with respect to copper may be due to a number of issues, including poorly defined tributary inputs, large errors in the prediction of TSS, and possible misrepresentation of copper fate and transport processes in the model. Copper is currently modeled as a contaminant associated with inorganic suspended solids. Some studies have suggested that dissolved organic carbon may play a role in copper fate and transport in freshwater aquatic systems (Shi et al. 1998, Kolak et al. 1999).

Further improvements in the model's capabilities will only come with additional data collection and further model testing and development. Following the recommendations in King County (2005b), one critical area to focus on is better quantification of ungauged surface and groundwater inputs, primarily of heat (i.e., temperature), dissolved solids (measured as specific conductance) and nutrients. Groundwater inputs to the river during summer low flow have been identified (Carey 2003) and gradual longitudinal increases in conductance during summer (King County 2005b) also provide evidence of direct and indirect (through groundwater fed tributaries) groundwater inputs to the river. These inputs have the potential to be cooler and have higher concentrations of dissolved solids and nutrients. Quantification of aquatic plant biomass and additional water surface profiles would also provide additional data for model testing and improvement. To these ends, a study of the river during low flow was planned and initiated in 2007 (King County 2007). The next Sammamish River modeling report will describe the results of this study and present model results and testing based on improvements made in light of the new data.

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Appendix A

Log-Linear regression approach used to estimate selected model constituent boundary conditions

Estimates of hourly constituent concentrations and flow were desired for tributary inputs to the Sammamish River CE-QUAL-W2 water quality model. The initial plan was to use constituent concentrations estimated from calibrated HSPF watershed models as the boundary conditions for our receiving water models. The watershed models, although developed, are not completely calibrated and do not yet provide accurate tributary constituent predictions for all river tributaries. Therefore, other methods needed to be developed in the interim to provide reasonably accurate estimates of tributary concentrations using available data. These tributary inputs are needed to calibrate the receiving water models to recent monitoring data.

Review of a number of constituent concentration time series for major tributaries in the Sammamish basin indicated that dissolved constituents could be reasonably estimated from linear interpolation of monthly observations (e.g., nitrate, ammonium, phosphate). However, constituents associated with particulates [e.g., total suspended solids (TSS), total phosphorus (TP), indicator bacteria, and copper] appeared to be more variable, most likely in response to rainfall-washoff processes that bring large amounts of particulates into the stream or that erode or resuspend particuates within the stream channel. Therefore, regression models that include the effect of flow on concentration were explored as a means to estimate hourly tributary constituent concentrations.

Log-linear multiple regression models have been used to represent tributary loads using flow and constituent concentration data (Cohn et al. 1992). Much of the research work on these models has been performed on data for Chesapeake Bay tributaries. The model of Cohn et al. (1992) required the estimation of 7 parameters: a constant, a quadratic fit to the logarithm of discharge (2 parameters), a quadratic fit to time (2 parameters), and a sinusoidal (first-order Fourier) function to remove the effects of annual seasonality (2 parameters) (see Equation 1).

Equation 1

$$\begin{aligned}\ln[C] \quad = \quad & \beta_o + \beta_1 \ln[Q/\tilde{Q}] + \beta_2 \left(\ln[Q/\tilde{Q}]\right)^2 + \beta_3[T-\tilde{T}] + \beta_4[T-\tilde{T}]^2 + \\ & \beta_5 \sin[2\pi T] + \beta_6 \cos[2\pi T] + \varepsilon\end{aligned}$$

The Washington State Department of Ecology has used a simplified version of this regression model to estimate daily fecal coliform loads for the Grays Harbor Fecal Coliform Total Maximum Daily Load (TMDL) Study (Pelletier and Seiders 2000) and to estimate watershed nutrient loads for the South Puget Sound Model Nutrient Study [http://www.ecy.wa.gov/programs/eap/spasm/index.html]. The Grays Harbor fecal coliform (FC) regression model (Equation 2) takes the form:

Equation 2

$$\log[FC] \quad = \quad \beta_o + \beta_1 \log[Q] + \beta_2 \sin[2\pi T] + \beta_3 \cos[2\pi T] + \varepsilon$$

These models are first used to predict daily concentrations from the record of daily flows, which require a re-transformation of the predicted logarithm of concentration back

into the original units of concentration. The re-transformation step has the potential to introduce a significant bias into the estimate of daily concentration. Much of the literature on the applications of these regression models has focused on their accuracy and bias and numerical methods to reduce bias (Duan 1983, Thomas 1985, Koch and Smillie 1986, Cohn et al. 1989, Gilroy et al. 1990, Cohn et al. 1992). Thomas (1985) and Koch and Smillie (1986) recommended Duan's (1983) "smearing estimate", which is a non-parametric re-transformation function appropriate for non-normal error distributions. The smearing estimate (K_{se}) is the mean value of the antilogs of the regression residuals. The predictive form of the regression equation (Equation 3) becomes:

Equation 3

$$FC = K_{se}(10^{(\beta_o + \beta_1 \log[Q] + \beta_2 \sin[2\pi T] + \beta_3 \cos[2\pi T])}$$

Brett et al. (2005) used a multivariate approach to predict daily total and soluble reactive phosphorus (TP and SRP, respectively) concentrations in four King County streams that were the focus of relatively high frequency sampling (daily TP and weekly SRP measurements) for a one year period (Aug. 2000- Aug. 2001). Brett et al. (2005) evaluated a number of regression parameters that incorporated factors associated with seasonal changes in baseflow, rapid changes in flow ("spikiness"), antecedent flow conditions, and rainfall.

Baseflow was estimated by fitting a 4th-order polynomial regression to the monthly running median value of the annual daily flow time series. Spikiness was estimated using the logarithm of the ratio of a day's flow divided by the preceding day's flow [i.e., Spikiness = $\log(flow_t/flow_{t-1})$]. Antecedent flow conditions were characterized by taking the logarithm of the ratio of the geometric mean flow on days 2-4 preceding a given day divided by the flow on that day [i.e., Antecedent flow = $\log(geomean(flow_{t2\ to\ t4})/flow_t)$]. The preceding day's flow was not included in the antecedent flow measure because of concern that this would make the antecedent index strongly correlated with the flow spikiness index. Their rainfall index was calculated as the mean of the rainfall for the preceding day and the day the stream sample was collected [i.e., rainfall = $mean(rainfall_{t-1}, rainfall_t)$]. The overall linear regression model was then:

Equation 4

$$\log[C] = Intercept + Baseflow + Spikiness + Antecedent + Rain$$

Sammamish River Tributary Constituent Concentrations

To estimate tributary constituent concentrations for the Sammamish River model, a combination of these approaches was evaluated. The general equation (Equation 5) used was:

Equation 5

$$\begin{aligned}\log[C] \quad = \quad & \beta_o + \beta_1 \log[Q] + \beta_2 Spikiness + \beta_3 Baseflow + \beta_4 Antecedent + \\ & \beta_5 \sin[2\pi T] + \beta_6 \cos[2\pi T] + \varepsilon\end{aligned}$$

However, in this case "baseflow" was more simply defined as the monthly running median value of the daily flow time series. This omitted the need to fit a 4th-order polynomial to the running median. Rainfall was omitted from the regression equation to minimize data requirements and the inclusion of rainfall seemed redundant considering the relationship between the spikiness and rainfall indices.

In general, it was found that inclusion of the Baseflow and Antecedent indices did not significantly improve the explanatory power of the regression models. Overall, the regression models were best at explaining the variation of TSS concentrations followed by FC and then TP concentrations. The model predictions for EC were not as good as those for FC, but this may be due more to the fewer number of observations available for EC – sampling for EC wasn't initiated until 1999. The predictive power of TP concentrations might be improved if model development focused on estimation of particulate P by subtracting SRP from observed TP concentrations.

A satisfactory regression model for total copper was not found using the approach outlined above. Some other approaches were explored using other regression variables. The best model found thus far is a simple linear regression using the model-predicted TSS concentrations for each tributary as the predictor variable.

Regression model statistics for the Big Bear Creek models are provided in Table A1. Modeled vs. predicted concentrations for Big Bear, Little Bear, North and Swamp creeks are shown in Figures A1-A4.

Calculation of Duan's K_{se} for each log-linear regression model resulted in smearing factors that were typically smallest for the Big Bear Creek models, ranging from 1.02 for TP to 1.36 for *E. coli* (Table A2). Among the four parameters modeled using the log-linear approach, the smearing factors were generally lowest for models of TP concentration (1.02-1.03) with higher factors calculated for TSS (1.09-1.22), FC (1.20-1.40), and EC (1.24-1.36).

Table A1. Log-linear multiple regression model statistics for Big Bear Creek

	Regression Statistics		Intercept	logQ	Spikiness	sin2piT	cos2piT
TSS	R Square	0.7912	0.28082	0.31802	1.5029	0.061055	-0.001069
	F	44.518					
	p-value	1.998e-15					
	Standard Error	0.031					
	Observations	133					
TP	R Square	0.7012	-1.2214	-	0.74151	-0.071261	-0.01106
	F	37.544					
	p-value	1.218e-12					
	Standard Error	0.0086					
	Observations	133					
FC	R Square	0.7910	2.1005	-	2.6823	-0.13972	-0.4949
	F	60.558					
	p-value	2.22e-16					
	Standard Error	0.081					
	Observations	132					
EC	R Square	0.6133	2.1029	-	2.1736	-0.12676	-0.46374
	F	25.379					
	p-value	5.55e-10					
	Standard Error	0.1542					
	Observations	68					
Cu	R Square	0.5633	1.4949	0.0334			
	F	25.795					
	p-value	5.73e-5					
	Standard Error	1.3994					
	Observations	36					

TSS = Total suspended solids; TP = Total phosphorus; FC = fecal coliform; Ent = Enterococcus; EC = *E. coli*

Table A2. Summary of Duan's smearing estimates.

Location	TSS	TP	FC	EC
Big Bear	1.09	1.02	1.21	1.36
Little Bear	1.22	1.03	1.33	1.26
North	1.12	1.02	1.40	1.24
Swamp	1.18	1.02	1.20	1.25

TSS = Total suspended solids; TP = Total phosphorus; FC = fecal coliform; EC = *E. coli;* NR = No regression model developed due to limitations of data/time/need

References:

Brett, M.T., S.E. Mueller, and G.B. Arhonditsis. 2005. A daily time series analysis of stream water phosphorus concentrations along an urban to forest gradient. Environmental Management 35(1):56-71. doi: 10.1007/s00267-003-0310-0

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Pelletier, G. and K. Seiders. 2000. Grays Harbor fecal coliform TMDL study. Washington State Department of Ecology, Olympia, WA. Publication No. 00-03-020.

[http://www.ecy.wa.gov/programs/eap/wrias/tmdl/ghfc/results.html]

Thomas, R.B. 1985. Estimating total suspended sediment yield with probability sampling. Water Res. Res. 21(9):1381-1388.

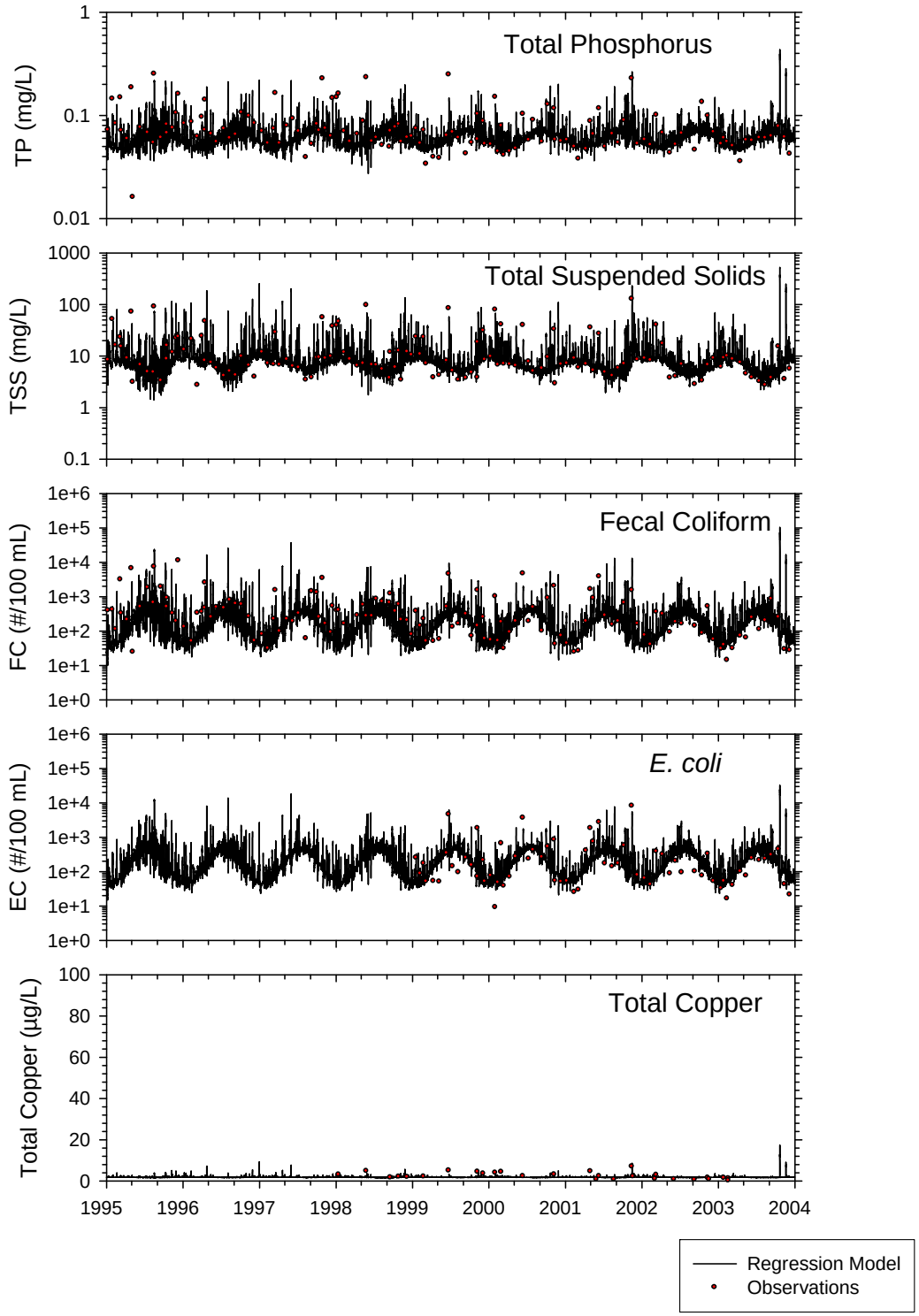

Figure A-1. Log-linear regression model results for Big Bear Creek, 1995-2003.

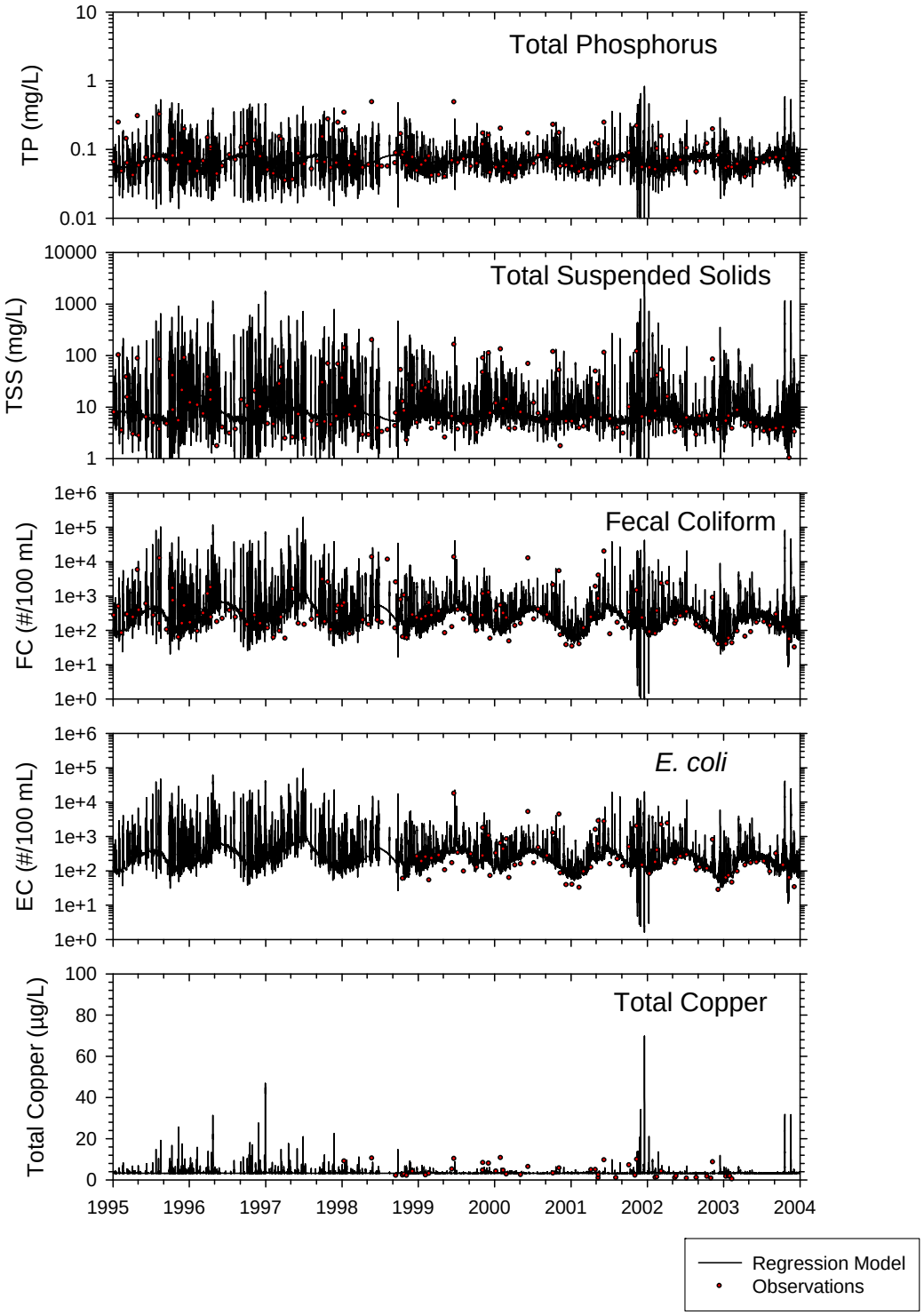

Figure A-2. Log-linear regression model results for Little Bear Creek, 1995-2003.

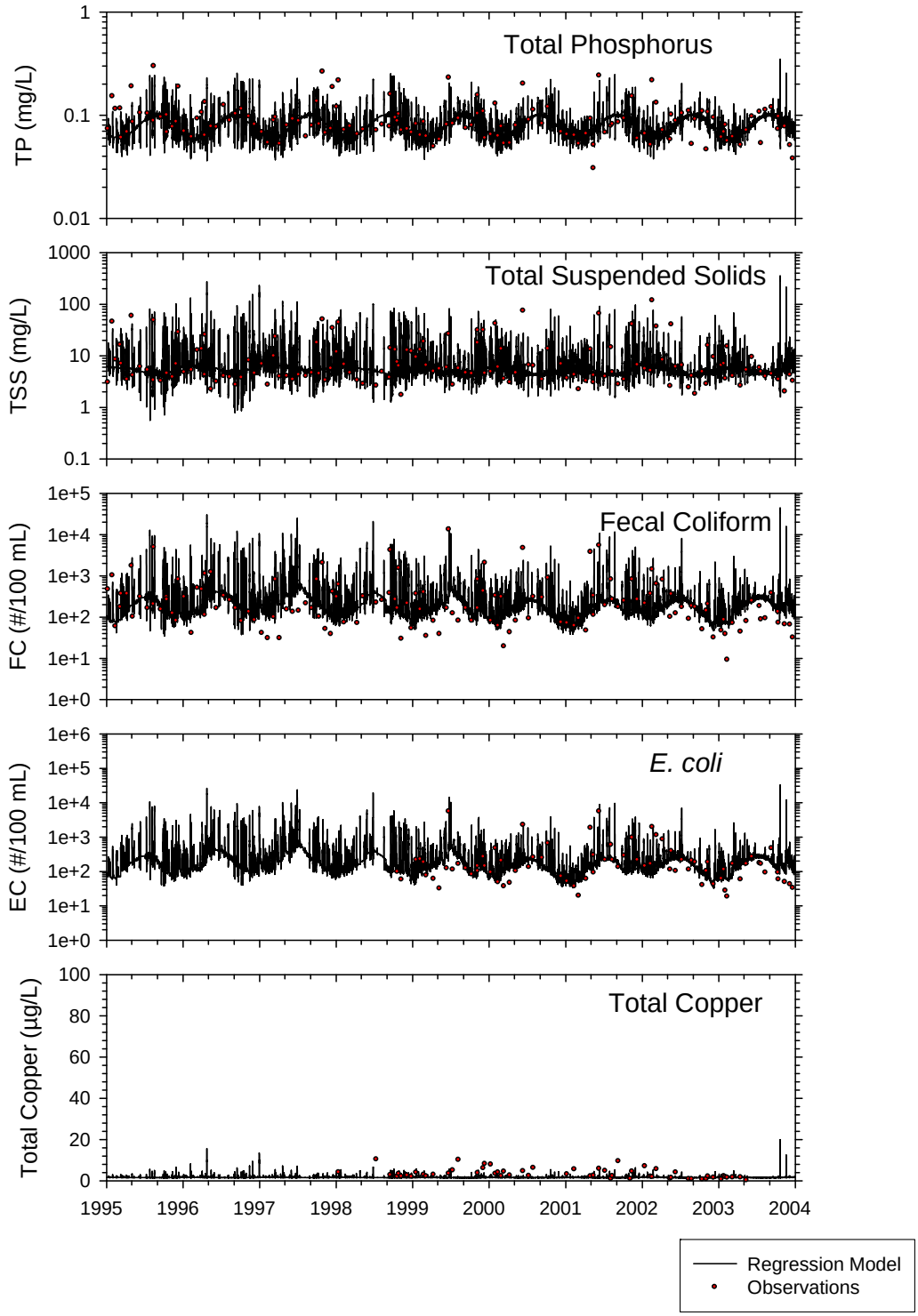

Figure A-3. Log-linear regression model results for North Creek, 1995-2003.

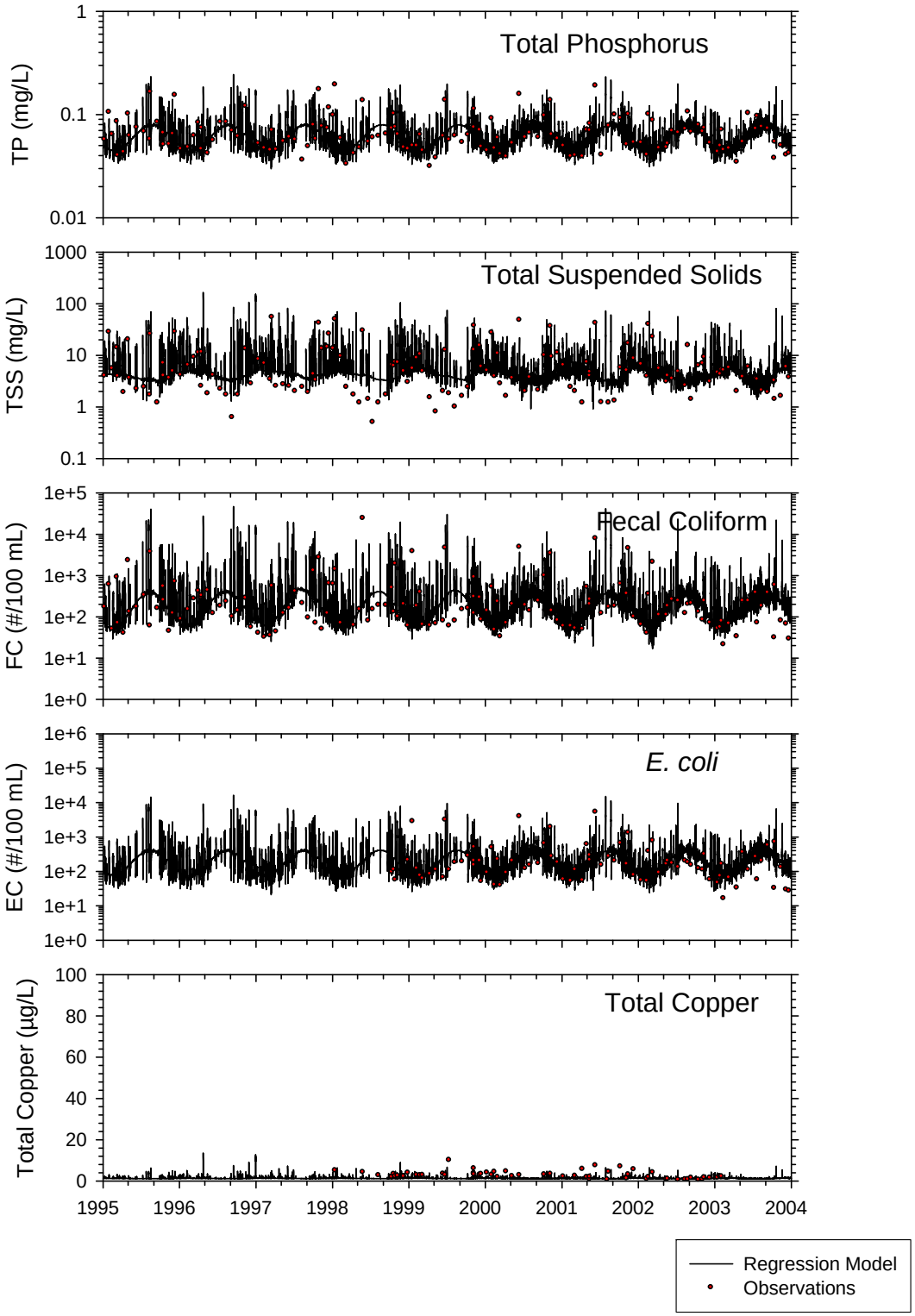

Figure A-4. Log-linear regression model results for Swamp Creek, 1995-2003.

Appendix B

Model Control Flags and Coefficients

Table 17 Model control file hydrodynamic and heat exchange flags and coefficients.

Heat Exchange									
Water Body	**SLHTC**	**SROC**	**RHEVAP**	**METIC**	**FETCHC**	**AFW**	**BFW**	**CFW**	**WINDFH**
WB 1	TERM	ON	OFF	ON	OFF	9.2	0.46	2	2
WB 2	TERM	ON	OFF	ON	OFF	9.2	0.46	2	2
Transport									
Water Body	**SLTRC**	**THETA**							
WB 1	ULTIMATE	0.55							
WB 2	ULTIMATE	0.55							
Hydrodynamic Coefficients									
Water Body	**AX**	**DX**	**CBHE**	**TSED**	**FI**	**TSEDF**	**FRICC**		
WB 1	1	1	0.3	13	0.01	1	MANN		
WB 2	1	1	0.3	13	0.01	1	MANN		
Eddy Viscosity									
Water Body	**AZC**	**AZSLC**	**AZMAX**						
WB 1	NICK	IMP	2						
WB 2	W2N	IMP	2						

KEY

NAME	VALUE	DEFAULT	DESCRIPTION
SLHTC	Character	ET	Specify either term-by term (TERM) or equilibrium temperature (ET) for surface heat exchange
SROC	Character	OFF	Read in observed surface solar radiation, ON or OFF
RHEVC	Character	OFF	Turns ON/OFF Ryan-Harleman evaporation formula
METIC	Character	OFF	Turns ON/OFF meteorological input data interpolation
FETCHC	Character	OFF	Turns ON/OFF fetch calculation
AFW	Real	9.2	*a* coefficient in wind speed formulation
BFW	Real	0.46	*b* coefficient in wind speed formulation
CFW	Real	2	*c* coefficient in wind speed formulation
WINDFH	Real	Wind	Wind speed measurement height (m) used in wind speed formulation (WINDH – moved to windh.npt to allow time varying wind speed measurement height)
SLTRC	Character	ULTIMATE	Transport solution scheme, ULTIMATE, QUICKEST, or UPWIND
THETA	Real	0.55	Time-weighting for vertical advection scheme
AX	Real	1	Longitudinal eddy viscosity, $m^2\ sec^{-1}$
DX	Real	1	Longitudinal eddy diffusivity, $m^2\ sec^{-1}$
CBHE	Real	0.3	Coefficient of bottom heat exchange, $W\ m^{-2}\ sec^{-1}$
TSED	Real	-	Sediment temperature, ^oC
FI	Real	0.01	Interfacial friction factor
TSEDF	Real	-	Heat lost to sediments that is added back to the water
FRICC	Character	CHEZY	Bottom friction formula, MANN or CHEZY
AZC	Character	W2	Form of the vertical turbulence closure algorithm, NICK, PARAB, RNG, W2, W2N, or TKE
AZSLC	Character	EXP	Specifies either implicit, IMP, or explicit, EXP, treatment of the vertical eddy viscosity in the longitudinal momentum equation
AZMAX	Real	1.00E-03	Maximum value for vertical eddy viscosity, $m^2\ sec^{-1}$

Table 18. Model control file light extinction flags and coefficients.

Light Extinction Coefficients						
EX COEF	**EXH2O**	**EXSS**	**EXOM**	**BETA**	**EXC**	**EXIC**
WB 1	0.25	0.01	0.01	0.45	OFF	OFF
WB 2	0.25	0.01	0.01	0.45	OFF	OFF
Algae Light Extinction Coefficients						
ALG EX	**EXA**	**EXA**	**EXA**			
	0.2	0.2	0.2			

KEY

NAME	VALUE	DEFAULT	DESCRIPTION
EXH2O	Real	0.25 or 0.45	Extinction for pure water, m-1
EXSS	Real	0.1	Extinction due to inorganic suspended solids, m-1
EXOM	Real	0.1	Extinction due to organic suspended solids, m-1
BETA	Real	0.45	Fraction or incident solar radiation absorbed at the water surface
EXC	Character	OFF	Read extinction coefficient, ON or OFF
EXIC	Character	OFF	If EXC = ON, Interpolate extinction coefficient, ON or OFF
EXA	Real	0.2	Algal light extinction, m-1

Table 19. Model control file generic constituent flags and coefficients.

Generic Constituents					
GENERIC	**CGQ10**	**CG0DK**	**CG1DK**	**CGS**	**CGSKD**
Tracer (CG 1)	0	0	0	0	0
Copper (CG2)	0	0	0	0	5
Fecals (CG3)	1.04	0	0.5	0.2	0
E. coli (CG4)	1.04	0	0.2	1	0

KEY

NAME	VALUE	DEFAULT	DESCRIPTION
CGQ10	Real	-	Arhennius temperature rate multiplier
CG0DK	Real	-	0-order decay rate, day^{-1}
CG1DK	Real	-	1st-order decay rate, day^{-1}
CGS	Real	-	Settling rate, m day^{-1}
GSKD	Real	-	Logarithm of the inorganic solids partition coefficient, log [L kg^{-1}] Note: Added as part of King County modification of model to include simple partitioning.

Table 20. Model control file inorganic suspended solids flags and coefficients.

Suspended Solids Settling and Resuspension			
S SOLIDS	**SSS**	**SEDRC**	**TAUCR**
SS# 1	10	OFF	0

KEY

NAME	VALUE	DEFAULT	DESCRIPTION
SSS	Real	1	Suspended solids settling rates, m day^{-1}
SEDRC	Real	OFF	Turns ON or OFF sediment resuspension
TAUCR	Real	1.00E-05	Critical shear velocity for sediment resuspension, m sec^{-1}

Table 21. Model control file algal flags and coefficients.

Algal constants									
ALGAL RATE	**AG**	**AR**	**AE**	**AM**	**AS**	**AHSP**	**AHSN**	**AHSSI**	**ASAT**
Diatoms (ALG1)	1.5	0.02	0.02	0.05	0.04	0.003	0.014	0.003	50
Greens (ALG2)	2.5	0.02	0.02	0.05	0.1	0.003	0.014	0	75
Cyanob. (ALG3)	0.5	0.02	0.02	0.01	0.02	0.003	0.01	0	100
Algal temperature constants									
ALGAL TEMP	**AT1**	**AT2**	**AT3**	**AT4**	**AK1**	**AK2**	**AK3**	**AK4**	
Diatoms (ALG1)	5	18	20	24	0.1	0.99	0.99	0.01	
Greens (ALG2)	10	30	35	40	0.1	0.99	0.99	0.01	
Cyanob. (ALG3)	10	35	40	50	0.1	0.99	0.99	0.01	
Algal stoichiometry									
ALG STOI	**ALGP**	**ALGN**	**ALGC**	**ALGSI**	**ACHLA**	**ALPOM**	**ANEQN**	**ANPR**	
Diatoms (ALG1)	0.001	0.02	0.45	0.18	55	0.8	2	0.001	
Greens (ALG2)	0.001	0.02	0.45	0	55	0.8	2	0.001	
Cyanob. (ALG3)	0.001	0.02	0.45	0	55	0.8	2	0.001	

KEY

NAME	VALUE	DEFAULT	DESCRIPTION
AG	Real	2	Maximum algal growth rate, day^{-1}
AR	Real	0.04	Maximum respiration rate, day^{-1}
AE	Real	0.04	Maximum algal excretion rate, day^{-1}
AM	Real	0.1	Maximum algal mortality rate, day^{-1}
AS	Real	0.1	Algal settling rate, m day^{-1}
AHSP	Real	0.003	Algal half-saturation for phosphorus limited growth, g m^{-3}
AHSN	Real	0.014	Algal half-saturation for nitrogen limited growth, g m^{-3}
AHSSI	Real	0	Algal half-saturation for silica limited growth, g m^{-3}
ASAT	Real	75	Light saturation intensity at maximum photosynthetic rate, W m^{-2}
AT1	Real	5	Lower temperature for algal growth, ^{o}C
AT2	Real	25	Lower temperature for maximum algal growth, ^{o}C
AT3	Real	35	Upper temperature for maximum algal growth, ^{o}C
AT4	Real	40	Upper temperature for algal growth, ^{o}C
AK1	Real	0.1	Fraction of algal growth rate at AT1
AK2	Real	0.99	Fraction of maximum algal growth rate at AT2
AK3	Real	0.99	Fraction of maximum algal growth rate at AT3
AK4	Real	0.1	Fraction of algal growth rate at AT4
AP	Real	0.005	Stoichiometric equivalent between algal biomass and phosphorus
AN	Real	0.08	Stoichiometric equivalent between algal biomass and nitrogen
AC	Real	0.45	Stoichiometric equivalent between algal biomass and carbon
ASI	Real	0.18	Stoichiometric equivalent between algal biomass and silica
ACHLA	Real	145	Ratio between algal biomass and chlorophyll a
APOM	Real	0.8	Fraction of algal biomass that is converted to organic matter when algae die
ANEQN	Integer	2	Equation number for algal ammonium preference
ANPR	Real	0.001	Algal half-saturation for ammonium

Table 22. Model control file epiphyton flags and coefficients.

Epiphyton constants								
EPI RATE	**EG**	**ER**	**EE**	**EM**	**EB**	**EHSP**	**EHSN**	**EHSSI**
EPI1	0.6	0.01	0.001	0.02	0	0	0	0
EPI HALF	**ESAT**	**EHS**	**ENEQN**	**ENPR**	**EPI_HCC**			
EPI1	275	50	2	0.001	10			
Epiphyton temperature constants								
EPI TEMP	**ET1**	**ET2**	**ET3**	**ET4**	**EK1**	**EK2**	**EK3**	**EK4**
EPI1	1	20	27	30	0.1	0.99	0.99	0.1
Epiphyton stoichiometry								
EPI STOI	**EP**	**EN**	**EC**	**ESI**	**ECHLA**	**EPOM**		
EPI1	0.001	0.02	0.45	0	50	0.8		

KEY

NAME	VALUE	DEFAULT	DESCRIPTION
EG	Real	2	maximum epiphyton growth rate, day^{-1}
ER	Real	0.04	maximum epiphyton respiration rate, day^{-1}
EE	Real	0.04	maximum excretion rate, day^{-1}
EM	Real	0.1	maximum mortality rate, day^{-1}
EB	Real	0.001	epiphyton burial rate, m day^{-1}
EHSP	Real	0.003	epiphyton half-saturation for phosphorus limited growth, g m^{-3}
EHSN	Real	0.014	epiphyton half-saturation for nitrogen limited growth, g m-3
EHSSI	Real	-	epiphyton half-saturation for silica limited growth, g m-3
ESAT	Real	75	light saturation intensity at maximum photosynthetic rate, W m^{-2}
EHS	Real	15	biomass limitation factor, g
ENEQN	Integer	2	ammonia preference factor equation (1 or 2)
ENPR	Real	0.001	nitrogen half-saturation preference constant, mg/L *only used if ENEQN = 2 is used*
EPI_HCC	Real	-	Epiphyton biomass half-saturation constant for effect on Manning's bottom friction, g m^{-3} Note: Added by King County to account for plan bottom friction
ET1	Real	5	Lower temperature for epiphyton growth, ^{o}C
ET2	Real	25	Lower temperature for maximum epiphyton growth, ^{o}C
ET3	Real	35	Upper temperature for maximum epiphyton growth, ^{o}C
ET4	Real	40	Upper temperature for epiphyton growth, ^{o}C
EK1	Real	0.1	Fraction of epiphyton growth rate at ET1
EK2	Real	0.99	Fraction of maximum epiphyton growth rate at ET2
EK3	Real	0.99	Fraction of maximum epiphyton growth rate at ET3
EK4	Real	0.1	Fraction of piphyton growth rate at ET4
EP	Real	0.005	Stoichiometric equivalent between epiphyton biomass and phosphorus
EN	Real	0.08	Stoichiometric equivalent between epiphyton biomass and nitrogen
EC	Real	0.45	Stoichiometric equivalent between epiphyton biomass and carbon
ESI	Real	0.18	Stoichiometric equivalent between epiphyton biomass and silica
ECHLA	Real	145	Ratio between epiphyton biomass and chlorophyll
EPOM	Real	0.8	Fraction of epiphyton biomass that is converted to organic matter when epiphyton die

Table 23. Model control file organic matter flags and coefficients.

Dissolved organic matter decay rates				
DOM	**LDOMDK**	**RDOMDK**	**LRDDK**	
WB 1	0.12	0.001	0.001	
WB 2	0.12	0.001	0.001	
Particulate organic matter decay rates				
POM	**LPOMDK**	**RPOMDK**	**LRPDK**	**POMS**
WB 1	0.08	0.001	0.001	0.5
WB 2	0.08	0.001	0.001	0.5
Organic matter stoichiometry				
OM STOIC	**ORGP**	**ORGN**	**ORGC**	**ORGSI**
WB 1	0.001	0.02	0.45	0
WB 2	0.001	0.02	0.45	0
Organic matter tempeature constants				
OM RATE	**OMT1**	**OMT2**	**OMK1**	**OMK2**
WB 1	4	30	0.1	0.99
WB 2	4	30	0.1	0.99

KEY

NAME	VALUE	DEFAULT	DESCRIPTION
LDOMDK	Real	0.1	Labile DOM decay rate, day^{-1}
RDOMDK	Real	0.001	Refractory DOM decay rate, day^{-1}
LRDDK	Real	0.01	Labile to refractory DOM decay rate, day^{-1}
LPOMDK	Real	0.08	Labile POM decay rate, day^{-1}
RPOMDK	Real	0.001	Refractory POM decay rate, day^{-1}
LRPDK	Real	0.01	Labile to refractory POM decay rate, day^{-1}
POMS	Real	0.1	POM settling rate, m day^{-1}
ORGP	Real	0.005	Stoichiometric equivalent between organic matter and phosphorus
ORGN	Real	0.08	Stoichiometric equivalent between organic matter and nitrogen
ORGC	Real	0.45	Stoichiometric equivalent between organic matter and carbon
ORGSI	Real	0.18	Stoichiometric equivalent between organic matter and silica
OMT1	Real	4	Lower temperature for organic matter decay, ^{o}C
OMT2	Real	25	Upper temperature for organic matter decay, ^{o}C
OMK1	Real	0.1	Fraction or organic matter decay rate at OMT1
OMK2	Real	0.99	Fraction or organic matter decay rate at OMT2

Table 24. Model control file nutrient flags and coefficients.

Nitrification constants				
AMMONIUM	**NH4R**	**NH4DK**		
WB 1	0	0.06		
WB 2	0	0.06		
Nitrification temperature constants				
NH4 RATE	**NH4T1**	**NH4T2**	**NH4K1**	**NH4K2**
WB 1	5	25	0.1	0.99
WB 2	5	25	0.1	0.99
Denitrification constants				
NITRATE	**NO3DK**	**NO3S**		
WB 1	0.05	0		
WB 2	0.05	0		
Nitrate temperature constants				
NO3 RATE	**NO3T1**	**NO3T2**	**NO3K1**	**NO3K2**
WB 1	5	25	0.1	0.99
WB 2	5	25	0.1	0.99
Silica constants				
SILICA	**DSIR**	**PSIS**	**PSIDK**	**PARTSI**
WB 1	0.1	0	0.3	0.2
WB 2	0.1	0	0.3	0.2

KEY

NAME	VALUE	DEFAULT	DESCRIPTION
PO4R	Real	0.001	Sediment release rate of phosphorus, fraction of SOD
PARTP	Real	0	Phosphorus partitioning coefficient for suspended solids
NAME	VALUE	DEFAULT	DESCRIPTION
NH4REL	Real	0.001	Sediment release rate of ammonium, fraction of SOD
NH4DK	Real	0.12	Ammonium decay rate, day^{-1}
NH4T1	Real	5	Lower temperature for ammonia decay, ^{o}C
NH4T2	Real	25	Lower temperature for maximum ammonia decay, ^{o}C
NH4K1	Real	0.1	Fraction of nitrification at NH4T1
NH4K2	Real	0.99	Fraction of nitrification at NH4T2
NO3DK	Real	0.03	Nitrate decay rate, day^{-1}
NO3S	Real	1	Denitrification rate from sediments, m day^{-1}
NO3T1	Real	5	Lower temperature for nitrate decay, ^{o}C
NO3T2	Real	25	Lower temperature for maximum nitrate decay, ^{o}C
NO3K1	Real	0.1	Fraction of denitrification rate at NO3T1
NO3K2	Real	0.99	Fraction of denitrification rate at NO3T2
DSIR	Real	0.1	Dissolved silica sediment release rate, fraction of SOD
PSIS	Real	1	Particulate biogenic silica settling rate, m sec^{-1}
PSIDK	Real	0.3	Particulate biogenic silica decay rate, day^{-1}
PARTSI	Real	0	Dissolved silica partitioning coefficient

Table 25. Model control file sediment flags and coefficients.

Sediment CO_2 release						
SED CO2	**CO2R**					
WB 1	2.5					
WB 2	2.5					
Sediment stoichiometry						
STOICH 1	**O2NH4**	**O2OM**				
WB 1	4.57	1.4				
WB 2	4.57	1.4				
STOICH 2	**O2AR**	**O2AG**				
ALG1	1.1	1.4				
ALG2	1.1	1.4				
ALG3	1.1	1.4				
STOICH 3	**O2ER**	**O2EG**				
EPI1	1.1	1.4				
Oxygen limitation						
O2 LIMIT	**O2LIM**					
0.1						
Sediment decay						
SEDIMENT	**SEDC**	**SEDPRC**	**SEDCI**	**SEDK**	**FSOD**	**FSED**
WB 1	ON	OFF	0	0.75	0.5	1
WB 2	ON	OFF	0	0.75	0.5	1
Sediment decay temperature constants						
SOD RATE	**SODT1**	**SODT2**	**SODK1**	**SODK2**		
WB 1	4	30	0.1	0.99		
WB 2	4	30	0.1	0.99		
Zero-order SOD constant						
S DEMAND	**SOD**					
	1.0	**All Segments**				

KEY

NAME	VALUE	DEFAULT	DESCRIPTION
CO2REL	Real	0.1	Sediment carbon dioxide release rate, fraction of SOD
O2NH4	Real	4.57	Oxygen stoichiometry for nitrification
O2OM	Real	1.4	Oxygen stoichiometry for organic matter decay
O2AR	Real	1.1	Oxygen stoichiometry for algal respiration
O2AG	Real	1.4	Oxygen stoichiometry for algal primary production
O2ER	Real	1.1	Oxygen stoichiometry for epiphyton respiration
O2EG	Real	1.4	Oxygen stoichiometry for epiphyton primary production
O2LIM	Real	0.1	Dissolved oxygen concentration at which anaerobic processes begin, g m^{-3}
SEDC	Character	OFF	Turns ON/OFF the first-order sediment compartment
PRNSC	Character	OFF	Turns ON/OFF printing sediment organic matter snapshot
SEDCI	Real	-	Initial sediment concentration, g m-2
SEDK	Real	-	Sediment decay rate, day-1
FSOD	Real	-	Fraction of the zero-order SOD rate used
FSED	Real	-	Fraction of the first-order SOD rate used
SODT1	Real	4	Lower temperature for zero-order SOD or first-order decay, oC
SODT2	Real	25	Upper temperature for zero-order SOD or first-order decay, oC
SODK1	Real	0.1	Fraction of SOD or sediment decay rate at SODK1
SODK2	Real	0.99	Fraction of SOD or sediment decay rate at SODK2
SOD	Real	-	Zero-order sediment oxygen demand for each segment, g O_2 m^{-2} day^{-1}

Table 26. Model control file reaeration flags and coefficients.

Reaeration parameters						
REAERATI	**ON TYPE**	**EQN#**	**COEF1**	**COEF2**	**COEF3**	**COEF4**
WB 1	RIVER	8	0	0	0	0
WB 2	LAKE	6	0	0	0	0

KEY

NAME	VALUE	DEFAULT	DESCRIPTION
REARC	Character	LAKE	Type of waterbody, RIVER, LAKE, or ESTUARY
EQN#	Integer	6	Equation number used for determining reaeration
COEF1	Real	-	User defined parameter
COEF2	Real	-	User defined parameter
COEF3	Real	-	User defined parameter
COEF4	Real	-	User defined parameter