Development of a Three-Dimensional Hydrodynamic Model of Lake Sammamish

(Version 1.0)

November 2008

King County
Department of Natural Resources and Parks
Water and Land Resources Division
Science Section
King Street Center, KSC-NR-0600
201 South Jackson Street, Suite 600
Seattle, WA 98104
dnr.metrokc.gov/wlr

Alternate Formats Available
206-296-7380  TTY Relay: 711
Development of a 3-Dimensional Hydrodynamic Model of Lake Sammamish (Version 1.0)

Submitted by:
Curtis DeGasperi
King County Water and Land Resources Division
Department of Natural Resources and Parks

King County
Department of Natural Resources and Parks
Water and Land Resources Division
Acknowledgements

The author acknowledges the assistance provided by the U.S. Army Corps of Engineers, Engineer Research and Development Center (ACOE-ERDC) in Vicksburg, Mississippi, to set up and modify the model they developed for Lake Washington for application to Lake Sammamish. The author specifically acknowledges the assistance of Sung-Chan Kim, Ph.D. and Carl Cerco, Ph.D., ACOE-ERDC. Thanks also to several internal reviewers (Jonathan Frodge, Debra Bouchard, Dean Wilson, and Jenée Colton) for constructive comments that helped improved the final report.

Citation

Table of Contents

Executive Summary................................................................. vii

1.0. Introduction........................................................................... 1

  1.1 Overview............................................................................. 1

  1.2 Study Area ......................................................................... 1

  1.3 Project Background............................................................ 3

  1.4 Goals and Objectives .......................................................... 5

  1.5 Historical Modeling Review.................................................. 5

2.0. Modeling Approach............................................................. 7

  2.1 Model Selection................................................................. 7

  2.2 Available Data Compilation, Review, and Identification of Data Gaps............ 8

  2.3 Additional Data Collection and Incorporation into Model............................... 8

  2.4 Selection of Periods for Model Calibration.............................................. 8

  2.5 Model Setup........................................................................ 8

    2.5.1 Grid Geometry .............................................................. 8

    2.5.2 Meteorology and Atmospheric Loading ............................................. 8

    2.5.3 Tributary Boundary Conditions ......................................................... 9

    2.5.4 Water Balance Including Precipitation and Evaporation........................ 9

  2.6 Model Testing and Calibration .............................................. 9

  2.7 Identification and Implementation of Model Refinements.......................... 10

  2.8 Final Testing and Calibration of Individual Models..................................... 10

  2.9 Integration of Receiving Water Models............................................. 11

   2.10 Integration of Receiving Water Models with Watershed Models .............. 11

3.0. Brief Description of Model................................................ 12
# Development of a 3-Dimensional Hydrodynamic Model of Lake Sammamish (Version 1.0)

## 4.0. Summary of Available Data for Model Setup and Calibration

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Bathymetric Data</td>
<td>14</td>
</tr>
<tr>
<td>4.2</td>
<td>Hydrologic Data</td>
<td>14</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Precipitation</td>
<td>14</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Tributary Inflow</td>
<td>19</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Lake Water Surface Elevations</td>
<td>19</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Lake Discharge</td>
<td>23</td>
</tr>
<tr>
<td>4.2.5</td>
<td>Water Balance</td>
<td>25</td>
</tr>
<tr>
<td>4.3</td>
<td>Water Quality Data</td>
<td>29</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Tributary Water Temperatures</td>
<td>29</td>
</tr>
<tr>
<td>4.3.2</td>
<td>In-lake Temperature Profiles</td>
<td>29</td>
</tr>
<tr>
<td>4.4</td>
<td>Meteorological Data</td>
<td>41</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Sea-Tac International Airport</td>
<td>44</td>
</tr>
<tr>
<td>4.4.2</td>
<td>NOAA Sandpoint Solar Radiation</td>
<td>48</td>
</tr>
<tr>
<td>4.4.3</td>
<td>University of Washington Atmospheric Sciences</td>
<td>48</td>
</tr>
<tr>
<td>4.4.4</td>
<td>South Lake Sammamish RUSS Buoy</td>
<td>48</td>
</tr>
</tbody>
</table>

## 5.0. Model Calibration

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
</tr>
</tbody>
</table>

## 6.0. Conclusions and Recommendations

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
</tr>
</tbody>
</table>

## 7.0. References

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>64</td>
</tr>
</tbody>
</table>

---

## Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Freshwater Program study area</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Lake Sammamish study area</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Lake Sammamish CH3D-Z model grid and cell depths</td>
<td>16</td>
</tr>
</tbody>
</table>
Figure 4  Selected precipitation gauge locations in the vicinity of Lake Sammamish ..............17

Figure 5  Daily total precipitation at Sea-Tac (A), observed Issaquah Creek discharge, HSPF-modeled runoff from remaining tributary basins, and lake stage (B), and comparison of the total gauges and HSPF-modeled discharge to the distributed flow required to balance the water budget (C). ........................................................................................................................................21

Figure 6  Selected King County and USGS stream and stage gauging locations ..................22

Figure 7  Tributary discharge and nearshore basin runoff assignments to the CH3D-Z model grid. ........................................................................................................................................23

Figure 8  Selected stage-discharge relationships for outflow over the Lake Sammamish weir ...24

Figure 9  Example of lake outlet stage-discharge hysteresis resulting from New Years 1997 storm. ........................................................................................................................................24

Figure 10  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 ...........26

Figure 11  Comparison of model-predicted and observed daily Lake Sammamish stage, 1995-2002. ........................................................................................................................................27

Figure 12  Annual average flow contribution from each component of the water budget described in the text (A) and the relative contribution of each inflow component (B). ......28

Figure 13  Locations of selected King County routine streams monitoring stations ..............31

Figure 14  Temperatures reported for selected Lake Sammamish tributaries as part of King County’s routine stream monitoring program, 1995-2002. ...............................................................................33

Figure 15  Comparison of Issaquah Creek continuous (15-minute) vs. routine grab (~monthly) temperature records, 2001-2003. ........................................................................................................34

Figure 16  Locations of selected King County Lake Sammamish and Sammamish River routine monitoring locations ........................................................................................................36

Figure 17  Selected temperature profiles from Lake Sammamish routine monitoring stations, 2002 ........................................................................................................................................37

Figure 18  Temperature profiles from Central Lake Sammamish routine monitoring station 0612, 2002 ........................................................................................................................................38

Figure 19  Near-surface (~1 m depth) temperature time series from Lake Sammamish routine monitoring station 0625 and Sammamish River at Marymoor Park (0486), 1995-2002. ....39
Figure 20  North Sammamish (SAMMN) RUSS buoy temperature color contour plots, 2000-2003........................................................................................................................................40

Figure 21  South Sammamish (SAMMS) RUSS buoy temperature color contour plots, 2000-2003........................................................................................................................................41

Figure 22  Selected meteorological stations in the vicinity of Lake Sammamish..................43

Figure 23  Sea-Tac meteorological data used in the Lake Sammamish model, 1995-2002........47

Figure 24  Solar Radiation data used in the Lake Sammamish model, 1995-2002.................49

Figure 25  Meteorological and solar radiation data recorded by the SAMMS RUSS buoy, 2000-2004........................................................................................................................................50

Figure 26  Comparison of initial model with additional turbulence suppression (solid blue lines) with final model without additional turbulence suppression (dashed red lines) – Lake Sammamish Station 0612, 1995. Observed temperature profiles (open circles) also shown..............................................................52

Figure 27  Comparison of 1995 observed daily average solar radiation to predictions from the original heat exchange program and CE-QUAL-W2. ..........................................................53

Figure 28  Box plot of hourly wind speeds recorded each year at Sea-Tac International Airport from 1995 to 2002..........................................................54

Figure 29  Comparison of modeled (lines) with observed (open circles) temperature profiles – Lake Sammamish Station 0612, 1995. ..................................................................................57

Figure 30  Comparison of modeled (lines) with observed (open circles) lake outlet surface temperature data – Lake Sammamish Stations 0625 and 0486, 1995-2002.........................58

Figure 31  Comparison of modeled with observed Lake Sammamish temperature data – Midlake (A) and Nearshore (B) stations, 1995-2002..........................................................60

Figure 32  Annual average error statistics for Lake Sammamish CH3D model temperature predictions by station, 1995-2002..........................................................61

Figure 33  Lake Sammamish CH3D model temperature prediction errors aggregated by depth for Midlake and Nearshore stations, 1995-2002..........................................................62
Tables

Table 1. Summary of Lake Sammamish CH3D-Z model grid statistics. ........................................ 16
Table 2. Selected precipitation gauges in the vicinity of Lake Sammamish and Sea-Tac International Airport. ........................................................................................................ 18
Table 3. Selected stream gauges in the Sammamish basin. ...................................................... 20
Table 4. Selected tributary monitoring locations in the Sammamish basin.......................... 30
Table 5. Lake Sammamish CH3D-Z tributary assignments and temperature data sources... 32
Table 6. Lake Sammamish CH3D-Z tributary assignments and temperature data sources... 35
Table 7. Selected meteorological stations in the vicinity of Lake Sammamish. ...................... 42
Table 8. Station history for Sea-Tac International Airport meteorological observations...... 45
Table 9. Cloud Cover code descriptions and translation from Octas to tenths....................... 46
Table 10. Summary of Lake Sammamish CH3D-Z Model Calibration Parameters. ............. 55
Table 11. Lake Sammamish CH3D-Z Model Temperature Prediction Errors – 1995-2002... 59

Appendices

Appendix A: Heat Exchange Program.................................................................................. A-1
Appendix B: Appendix Figures ............................................................................................. B-1
EXECUTIVE SUMMARY

As part of King County’s Freshwater Program – a capital project designed to develop scientific tools to better understand the Sammamish-Washington and Green-Duwamish watershed systems, a 3-dimensional hydrodynamic model of Lake Sammamish was developed. An existing coupled 3-D hydrodynamic and water quality modeling framework originally developed for the Chesapeake Bay Program (CH3D-Z and CE-QUAL-ICM) was selected for application to Lake Sammamish, Washington, and Union. Initial development and testing of the models on Lake Washington by the U.S. Army Corps of Engineers Waterways Experiment Station (ACOE-WES) resulted in a modeling system suitable for application to lakes (Cerco et al. 2003, Johnson et al. 2003). The CH3D-Z model code used in the ACOE-ERDC Lake Washington application was used with minor modifications to simulate Lake Sammamish hydrodynamics. The development (including minor modifications), calibration, and testing of the Lake Sammamish model is described in this report. The current version of the model is capable of reliably reproducing the seasonal and spatial thermal dynamics of the lake based on comparison to routine temperature profile data collected between 1995 and 2002. However, the model does produce systematic seasonal, interannual, and spatial (primarily vertical) errors that will require further data collection, testing, and refinement to reduce. Nonetheless, the model represents one of several potentially useful tools to evaluate the effects of land use and climate change on the aquatic resources of King County.
All models are wrong. Some models are useful.


All models are wrong, but some are useful.


http://www.boomer.org/pkin/PK01/PK2001250.html

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]

http://www2.ncsu.edu/ncsu/CIL/WRRI/news/ma02dirforum.html
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) [now 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. These two 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 SWAMP study area have been the focus of long-term limnological investigations for several decades. King County is currently developing hydrodynamic and water quality models of these lakes and the Sammamish River as part of the Freshwater Program.

This report documents the development of a three-dimensional hydrodynamic model of Lake Sammamish – one modeling component of a planned integrated water resource modeling system (King County 2004). The model selected for this effort was a 3-dimensional hydrodynamic model (Curvilinear Hydrodynamics in Three Dimensions – Z Plane [CH3D-Z]). The CH3D-Z model has been coupled to a 3-dimensional water quality model (CE-QUAL-ICM) of the lake. The development of the CE-QUAL-ICM model is the subject of a separate report (in progress).

1.2 Study Area

The Lake Sammamish study area includes a number of small tributary basins draining to the eastern and western shores of the lake and Tibbetts and Issaquah Creek basins draining into the southern end of the lake (Figure 2). The lake discharge at the north end of the lake is controlled by a broad-crested weir, which defines the beginning of the Sammamish River.

The total basin drainage area covers approximately 230 km² (excluding the lake surface). Issaquah Creek is the largest single tributary basin at 145 km². Although the Issaquah Creek basin includes the urban center of the town of Issaquah, about 70 percent of the Issaquah basin is forested (albeit second and third growth) based on King County’s 1995 land cover analysis. The Tibbetts Creek basin is also 70 percent forested. The southern area of the Lake Sammamish drainage is often referred to as the “Issaquah Alps” due to the high relief resulting from a westerly extension of the Cascade Mountains into the Puget Sound Lowlands. Elevations in the Issaquah Creek basin range from 8 m above mean sea level at the lake normal pool elevation to about 900 m at the top of Tiger Mountain in the Issaquah Creek basin. Squak Mountain (188 m) is drained by both Issaquah and Tibbetts Creeks. Cougar Mountain (138 m) is drained by Tibbetts and Lewis Creeks.
Figure 1 Freshwater Program study area.
Land cover in the east and west sub-basins is dominated by low- and medium-intensity development. The drainages on the western flank of the lake are more highly developed (20 percent forest cover remaining) due to the greater proximity to the urban center of Bellevue. The drainages on the east side of the lake have developed rapidly over the last 10 years with about 40 percent forest cover remaining. Due to the relatively large contribution of the Issaquah and Tibbetts Creek basins to the total drainage area, overall 68 percent of the Lake Sammamish drainage remains forested.

Welch et al. (1980) report that the lake itself has a surface area of 19.8 km², holds approximately 3.5 x 10⁸ m³ of water, and has a mean residence time of 1.8 yr. The lake has a maximum depth of about 32 m and a mean depth of 17.7 m (Welch et al. 1980). The lake is an elongated fiord-like trough about 13 km long oriented along a north-south axis reflecting its glacial provenance. The lake typically stratifies thermally beginning in May and de-stratifies in November. As the lake stratifies, the hypolimnion becomes progressively depleted of oxygen resulting in anaerobic bottom waters in late summer. During winter when the lake is oxygenated and relatively isothermal, temperatures typically do not go below 4 °C, although it has been reported that the lake was completely frozen over in January 1950 (http://www.lakesamm.com/history/bigfreeze.asp).

The lake basin has undergone a fairly dramatic transformation beginning in the 1860s with the first European-American settlements along the lake shore. Hop farming and then logging, dairies and coal and clay mining were the primary endeavors of these settlers (Fish 1967). By 1940 a secondary wastewater treatment plant (WWTP) was built for the town of Issaquah with a capacity of 0.15 MGD (Lazoff 1980). By 1960, Issaquah Creek was receiving effluent from the Issaquah WWTP, a milk processing plant, a state fish hatchery (established in 1936) and runoff from sand and gravel operations.

Based on studies conducted by Isaac et al. (1966) on Lake Sammamish and similar studies and effort to divert secondary effluent from nearby Lake Washington (Edmondson 1968, 1969), wastewater from the Issaquah WWTP and the milk processing plant were completely diverted from the lake by 1968. Lake Washington quickly recovered (Edmondson 1994), while the recovery of Lake Sammamish did not progress as quickly as expected based on flushing alone (Welch 1975, Welch et al. 1977). The delayed recovery of Lake Sammamish is well documented and has been attributed to sediment-nutrient interactions and the relatively smaller proportion of the total P load that was diverted (Birch et al. 1980; Welch 1985; Welch et al. 1980, 1986). Even before wastewater was completely diverted from the lake, concern was raised that rapid development of the basin would offset water quality benefits obtained from wastewater diversion (Kirkpatrick 1967). Concerns about the effect of basin development on lake water quality have continued to the present day (Howe 1979, Welch et al. 1986, King County 1995, Perkins et al. 1997).

### 1.3 Project Background

The U.S. Army Corps of Engineers, Engineer Research and Development Center (ACOE-ERDC) has developed a 3-dimensional water quality model (CE-QUAL-ICM) of Lake Washington for King County (Johnson et al. 2003, Cerco and Noel 2003). Dispersion and
advection of water quality constituents in the water quality model is based on output from a hydrodynamic model of the lake (Curvilinear Hydrodynamics in Three Dimensions [CH3D]).

**Figure 2** Lake Sammamish Study Area

- Incorporated area
- Study area boundary

**Figure 2 Lake Sammamish study area.**
1.4 Goals and Objectives

The overall goal of this modeling effort is the development and calibration of receiving water-quality models that simulate water movement (hydrodynamics) and eutrophication processes and their effects on dissolved oxygen and phytoplankton biomass. The models will also 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 are 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 will be used to supply data where field data are 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

Lake Sammamish has been the focus of water quality modeling efforts since the early 1970s beginning with the development of a vertical one-dimensional temperature and water quality model of the lake (Tang 1973, 1975). Findings from this effort can be summarized (Tang 1975):

- Use of regional wind data from Sea-Tac Airport required adjustments (i.e., reduction) of wind speed to match observed temperature profiles
- The model was very sensitive to the light extinction coefficient, which was input as a monthly average value
- Advective heat transfer (heat flux from rainfall and tributaries) was estimated to be small and was neglected in the simulations
- Wind speed determined the mixing depth in April-May and solar radiation controlled mixing depth in the summer
- Mixing depth was strongly affected by thermal convection
Although this model of Lake Sammamish was considered quite comprehensive and flexible and to be computationally efficient (i.e., not require inordinate computing time) (Tang 1975), later modeling efforts focused primarily on simpler non-steady state box models of total phosphorus (TP) (Shuster 1985, Butkus 1987). The goal of these modeling efforts was to evaluate the impact of stormwater controls on in-lake phosphorus concentrations under forecasted (year 2000) development levels. Empirical relationships were used to translate model predictions of future lake TP (bioavailable P in Butkus’ study) concentrations into chlorophyll $a$ and Secchi transparency – more relevant water quality management indicators.

A vertical 2-layer TP box model was developed in the mid-1990s and coupled with a watershed export coefficient/construction runoff model to predict the lake’s response to future development of the basin (King County 1995, Perkins et al. 1997). Empirical relationships were again used to translate model predictions of future lake TP concentrations into chlorophyll $a$ and Secchi transparency.

The current modeling effort is essentially a return to the initial modeling approach to mechanistically simulate lake temperature and the ecological response (algal biomass and transparency) to nutrient inputs to the lake. Thirty years later, although not new, concerns about the fate, transport, and effect of contaminants (trace metals and synthetic organic compounds) and fecal contamination are also on the minds of the public and water quality managers. Therefore, the current modeling effort includes simulation of trace metals and organic contaminant fate and transport.
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 resources followed by testing and model refinement. However, the application of models as an aid in management decision making typically requires a more finite project timeline. 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.

A relatively finite timeline will be achieved through the following steps:

- Develop new models or select existing models for project application (Existing models have been 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 individual models
- 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 Lake Sammamish hydrodynamic 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 coupled 3-D hydrodynamic and water quality modeling framework originally developed for the Chesapeake Bay Program (CH3D-Z and CE-QUAL-ICM) was selected for application to Lake Sammamish, Washington and Union. Initial development and testing of the models on Lake Washington by the U.S. Army Corps of Engineers Waterways Experiment Station (ACOE-WES) has resulted in a modeling system suitable for application to lakes (Cerco et al. 2003, Johnson et al. 2003). The CH3D-Z model code used in the ACOE-ERDC Lake Washington application was used with minor modifications (described below) to simulate Lake Sammamish hydrodynamics.
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 hydrodynamic model of Lake Sammamish, DeGasperi (2001) recommended the collection of continuous temperature data near the mouth of Issaquah Creek to better establish the inflow temperature of the largest tributary to the lake. Continuous temperature monitoring near the mouth of Issaquah Creek began in August 2001.

2.3 Additional Data Collection and Incorporation into Model

As additional data become available, they will be incorporated into the models. For example, a Major Lakes Hydrodynamic Study that includes current meter, thermistor chain, and vertical profiling of temperature, fluorescence, and particle size distribution was conducted on Lake Washington and Lake Sammamish (Schock 2002). The Lake Sammamish data collection began in mid-2002 and continued through the end of 2003. These data (primarily current meter and thermistor chain data) will be used to evaluate the model in the near future.

2.4 Selection of Periods for Model Calibration

The Lake Washington CH3D-Z model was initially setup and calibrated to temperature profile data from the period 1995-1997. Due to the limitations of the available data from that period (temperature profiling frequency was increased in more recent years), the Lake Sammamish model was set up and calibrated to the available 1995-2002 data. This provides eight years of routine (monthly to twice monthly) temperature profile data for model testing and calibration.

2.5 Model Setup

2.5.1 Grid Geometry

The foundation of a numerical water quality model is the specification of the grid geometry. Raw depth data from a recent bathymetric study of Lake Sammamish (July 1996) provided in electronic format by JC Headwaters, Inc. were used to define the depths of the defined model grid cells.

2.5.2 Meteorology and Atmospheric Loading

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.

Meteorological data have also been collected by King County from a Remote Underwater Sampling System (RUSS) buoy located on Lake Sammamish since July 2000, but due to frequent data gaps and uncertain quality of the data, these data have not been incorporated into the development of the current model. Potential use of the available RUSS data for model testing and calibration is planned for 2006.

2.5.3 Tributary Boundary Conditions

Input files of the tributary flow and temperature in the appropriate units and format were prepared using available routine temperature monitoring and gauging data and HSPF models of daily average flow for streams that are not typically monitored. Not all tributaries to Lake Sammamish are gauged and even fewer have detailed temperature records associated with them. Therefore, assumptions and approximations were required to assign a daily flow and temperature to each tributary inflow boundary.

The current version of the Lake Sammamish model includes 19 discrete tributary inflows including Issaquah Creek and 1 outflow representing the Sammamish River.

2.5.4 Water Balance Including Precipitation and Evaporation

Daily tributary inflows, lake outflow, and direct precipitation/evaporation at the lake surface were specified using a combination of observations, models, and default time series. Detail regarding the available data and methods are provided in Section 4.0 below.

2.6 Model Testing and Calibration

Once the model boundary conditions were established, the model was executed to simulate each year and compared to the available routine temperature profile data. Model calibration was conducted primarily by modifying the model code to better simulate the suppression of turbulent mixing by thermal density stratification and adjustment of the wind speed observed at Sea-Tac International Airport to better represent local wind conditions. The modification of the CH3D-Z turbulence suppression code was performed by ACOE-ERDC for the development of the Lake Washington CH3D-Z application (Johnson and Kim 2004). Model calibration was complete when no further significant improvement in the model fit could be made through an annual Wind Adjustment Factor, which adjusted the observed Sea-Tac wind speeds to account for differences between wind measured at Sea-Tac and winds that occur on the lake. It is believed that the need for wind speed adjustment is primarily due to sheltering of the lake from the predominant southwesterly winds by elevated topography around the southern end of the lake.

A number of model error statistics were computed and aggregated by parameter, season, location, and depth 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. Examples of representative model error statistics are provided below.

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

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

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

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

\[
REM = \frac{\sum_{n=1}^{N} |P_n - O_n|}{\sum_{n=1}^{N} O_n} \times 100 \quad \text{(relative error of the mean, percent)}
\]

### 2.7 Identification and Implementation of Model Refinements

As a result of model development work to date, a number of possible model refinements/additions to the Lake Sammamish CH3D-Z model have been identified and include:

- A conservative dye tracer.
- A lagrangian particle tracer
- The implementation of a downstream weir algorithm that would predict lake outflow given inflows. Outflow rate, temperature, tracer, and salinity would be written to an output file.
- Allow temperature and tracer inputs to be associated with distributed inflows. Ideally, code would allow control of the placement and distribution of these ungauged surface or groundwater inflows (or outflows).
- Allow tributary inflows to be placed into the grid layer most closely corresponding to the density of the inflow.
- Internally calculate the equilibrium heat exchange coefficient, equilibrium temperature, and evaporation rate within the model code to facilitate changing meteorological forcing in the model. Currently, these inputs are derived from observations of wind speed, air and dew point temperature, solar radiation, and cloud cover for input to the model.

### 2.8 Final Testing and Calibration of Individual Models

Setup and comparison to data collected in 2003 (primarily hydrodynamic data for Lake Sammamish) will provide a final test of the CH3D-Z model prior to initial integration and application. These comparisons will be the subject of a separate report.
2.9 **Integration of Receiving Water Models**

Integration of the Lake Sammamish model with the Sammamish River model will require the translation of the CH3D temperature (and flow if predicted by a modified model) and CE-QUAL-ICM constituent concentrations at the outlet of Lake Sammamish to the upstream boundary input file formats used by CE-QUAL-W2. Some translation between the CE-QUAL-ICM and CE-QUAL-W2 state variables will also be required.

2.1 **Integration of Receiving Water Models with Watershed Models**

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-ICM or CE-QUAL-W2 state variables will also be required.
3.0. BRIEF DESCRIPTION OF MODEL

CH3D is capable of modeling horizontal and vertical circulation induced by surface heat exchange, tide, wind, density effects (salinity and temperature), freshwater inflows, turbulence, and the effect of the earth’s rotation. The CH3D model was originally developed by Sheng (1986) using a vertical sigma-stretch grid. The vertical Cartesian grid (or Z-plane) version of CH3D evolved from the application by ACOE-ERDC of CH3D to Chesapeake Bay (Johnson et al. 1991). As the name implies, the horizontal CH3D grid is curvilinear (i.e., boundary-fitted) to best represent deep channels and flow along irregular shorelines. The development of the Lake Washington CH3D-Z model and a user’s manual for the Lake Washington application have been prepared by Johnson et al. (2003) and Johnson and Kim (2004), respectively.

A two-equation \( (k-\varepsilon) \) turbulence closure model is employed in CH3D-Z to represent vertical turbulent mixing. The eddy viscosity and eddy diffusivity turbulence terms are derived from the computation of kinetic energy \( (k) \) and energy dissipation \( (\varepsilon) \) due to the effects of surface wind shear, bottom shear, velocity gradient turbulence production, turbulent energy dissipation, and density stratification. Since vertical momentum is neglected to facilitate the solution of the finite difference equations (hydrostatic assumption), convective mixing is accounted for by checking the vertical density distribution after each time step. At locations where the water column is unstable, the maximum vertical eddy coefficients are applied to simulate convective mixing in a diffusive manner.

An externally processed equilibrium temperature and heat exchange coefficient time series is used to simulate thermal heat exchange at the lake surface. The pre-processing of meteorological data (air temperature, dew point, wind speed and direction, and cloud cover) into the model input file is documented in Appendix A. The preprocessing program originally developed by ACOE-ERDC for the Lake Washington application (Johnson et al. 2003) was modified for the Lake Sammamish application. The modifications included:

- Combining the pre-processing for surface wind forcing and surface heat exchange into a single program that would create CH3D and CE-QUAL-ICM meteorological input files from a single data source.

- Creating hourly input data rather than averaging the heat exchange input over portions of a day (4-hour averages were used in the ACOE-ERDC Lake Washington heat exchange input file).

- Scaling wind speed observations from the reported observation height to appropriate heights for input to the surface wind shear (10 m) and evaporative wind function (2 m) routines (Hsu et al. 1994).

- Allowing for reduction or increase in wind speed (Wind Adjustment Factor) to account for systematic differences between the off-site wind observations and wind over the lake.
The surface drag coefficient computation used in CH3D to calculate surface shear stress from wind was also modified slightly so that the minimum value allowable was 0.001 with no upper limit, which is similar to the current Puget Sound Princeton Ocean Model (POM) code. Mellor and Blumberg (2004) provide a discussion of the calculation of the surface drag coefficient.

In the current version of the model, surface evaporation rate is supplied in an input file to the model. Therefore, the evaporation rate used to model the mass transfer of water from the surface of the lake is uncoupled from the evaporative heat flux computed for the external equilibrium heat exchange input file. The daily evaporation rate used in the ACOE-ERDC Lake Washington application (Johnson et al. 2003) was used in the Lake Sammamish application.

Daily rainfall on the lake surface is also provided in an input file, but the heat flux associated with rainfall is not currently considered in the model. Similarly, the current version of the model allows for a distributed inflow to the lake surface to account for un-gauged surface runoff along the lake shoreline, but the heat flux (and momentum) associated with the distributed inflow is not considered.

The CH3D-Z model includes code for coupling the hydrodynamic model with the CE-QUAL-ICM water quality model. The coupling of the Lake Washington hydrodynamic model with CE-QUAL-ICM has been documented by Cerco and Noel (2003). A description of the coupling of CH3D-Z to CE-QUAL-ICM for Lake Sammamish will be described in the water quality model application report (in progress).
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. Data from a recent bathymetric study of Lake Sammamish (July 1996) provided in electronic format were used to define the depths of the defined model grid cells. The raw survey water depth data provided by JC Headwaters were normalized to the National Geodetic Vertical Datum of 1929 (NGVD29) by determining the average daily water surface elevation during July 1996 from the U.S. Geological Survey (USGS) gauge at Vasa Park on Lake Sammamish (12122000). These data were then merged with the 7.5 minute 10-m horizontal resolution Digital Elevation Models (DEMs) available from the USGS for the area surrounding Lake Sammamish. Surfer™ version 7.0 was then used to interpolate the raw data into a gridded bathymetry file (44 x 44 m horizontal resolution) suitable for use in developing the model grid. The DEM was then adjusted so that 8.08 m NGVD29 (the Lake Sammamish normal pool elevation) was equal to zero elevation—a requirement of the CH3D model equivalent to setting mean sea level equal to zero. A boundary-fitted model grid was then developed in the Surface Water Management System (SMS) version 7.0 using guidance and additional FORTRAN post-processing programs provided by ACOE-ERDC. The SMS software performed the interpolation of the processed bathymetric data into average water depths relative to normal pool elevation in each model grid cell. The boundary-fitted model grid and average cell depths are shown in Figure 3.

The surface grid layer in which the computational water surface must reside was set to a vertical thickness of 1.52 m and sub-surface layers were set to a thickness of 0.91 m. Additional model grid summary information is provided in Table 1. The normal pool elevation of 8.08 m resides 0.6 m below the top of the model surface grid layer.

4.2 Hydrologic Data

4.2.1 Precipitation

Precipitation data are currently available from a number of locations within the Lake Sammamish Basin (Table 2, Figure 4), but with the exception of the Tibbetts Creek gauge these data do not span the selected model calibration period of 1995-2002. The Tibbetts Creek gauge is approximately 54 m above the lake surface and is likely influenced by the steep local topography. Therefore, daily precipitation measured at Sea-Tac International Airport (available for 1950-2003) were used in the initial model development. West Consultants (2004) recently conducted a long-term (1989-2002) water balance on Lake Sammamish using Sea-Tac precipitation, but they adjusted these observations based on the ratio of local to Sea-Tac annual precipitation. Adjustment of Sea-Tac precipitation to better represent local lake surface precipitation is planned for the next version of the model. Adjustment will likely be based on the PRISM (Parameter-elevation Regressions on Independent Slopes Model) annual isohyetal maps.
for the area (http://www.ocs.orst.edu/prism/docs/overview.html) or U.S. Department of Agriculture 1961-1990 annual precipitation isohyets, which would result in an approximate 15 percent increase in daily Sea-Tac precipitation totals. The Sea-Tac daily precipitation totals (1995-2002) are shown in Figure 5.
Figure 3  Lake Sammamish CH3D-Z model grid and cell depths.

Table 1.  Summary of Lake Sammamish CH3D-Z model grid statistics.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Computational Cells</td>
<td>4,283</td>
</tr>
<tr>
<td>Number of Surface Cells</td>
<td>249</td>
</tr>
<tr>
<td>Surface Layer Thickness (DELTAZM)</td>
<td>1.52 m (5 ft)</td>
</tr>
<tr>
<td>Sub-surface Layer Thickness (DELTAZ)</td>
<td>0.91 m (3 ft)</td>
</tr>
<tr>
<td>Maximum number of layers (KMAX)</td>
<td>30</td>
</tr>
<tr>
<td>Average Cell Area</td>
<td>0.08 km² (19.8 ac)</td>
</tr>
<tr>
<td>Average Cell Length</td>
<td>280 m (920 ft)</td>
</tr>
<tr>
<td>Number of tributary inflow points</td>
<td>19</td>
</tr>
</tbody>
</table>
Figure 4  Selected precipitation gauge locations in the vicinity of Lake Sammamish.
Table 2. Selected precipitation gauges in the vicinity of Lake Sammamish and Sea-Tac International Airport.

<table>
<thead>
<tr>
<th>Site Code</th>
<th>Site Name</th>
<th>Northing</th>
<th>Easting</th>
<th>Date Installed</th>
<th>Date Removed</th>
<th>Elevation in meters (NGVD 1929)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBAN #24233</td>
<td>Sea-Tac International Airport</td>
<td>167684 †</td>
<td>1273425 †</td>
<td>1-Nov-44</td>
<td>active</td>
<td>112.8 (4/2/02- ) 121.9 (1/50-4/02)</td>
</tr>
<tr>
<td>MARY</td>
<td>Marymoor Park I&amp;I Rain Gage</td>
<td>244679</td>
<td>1323348</td>
<td>1-Oct-00</td>
<td>active</td>
<td>11</td>
</tr>
<tr>
<td>FACT</td>
<td>Factoria I&amp;I Rain Gage</td>
<td>215523</td>
<td>1313495</td>
<td>1-Oct-00</td>
<td>active</td>
<td>39</td>
</tr>
<tr>
<td>63u</td>
<td>Lewis Creek Rain Gauge</td>
<td>207701</td>
<td>1328002</td>
<td>01-Oct-88</td>
<td>11-Sep-89</td>
<td>59</td>
</tr>
<tr>
<td>67u</td>
<td>Tibbetts Creek Rain Gauge</td>
<td>194552</td>
<td>1336632</td>
<td>1-Oct-87</td>
<td>active</td>
<td>62</td>
</tr>
<tr>
<td>18Y (ml3)</td>
<td>Mystic Lake Rain Gauge East</td>
<td>231313</td>
<td>1346600</td>
<td>01-Nov-00</td>
<td>active</td>
<td>111</td>
</tr>
<tr>
<td>SAMP</td>
<td>Sammamish Plateau I&amp;I Rain Gage</td>
<td>214016</td>
<td>1346251</td>
<td>17-Oct-00</td>
<td>active</td>
<td>116</td>
</tr>
<tr>
<td>46v</td>
<td>Yellow Lake Rain Gauge</td>
<td>210692</td>
<td>1348656</td>
<td>01-Oct-90</td>
<td>30-Sep-95</td>
<td>123</td>
</tr>
<tr>
<td>46u</td>
<td>Black Nugget Rain Gauge</td>
<td>205545</td>
<td>1355585</td>
<td>1-Oct-87</td>
<td>30-Sep-99</td>
<td>194</td>
</tr>
<tr>
<td>63v</td>
<td>Cougar Mountain Park Rain Gauge</td>
<td>204116</td>
<td>1327674</td>
<td>01-Oct-92</td>
<td>30-Sep-97</td>
<td>234</td>
</tr>
<tr>
<td>63y</td>
<td>Cougar Mountain Rain Gauge</td>
<td>199945</td>
<td>1327971</td>
<td>17-Oct-94</td>
<td>active</td>
<td>442</td>
</tr>
<tr>
<td>HEAT</td>
<td>Heathfield</td>
<td>213609</td>
<td>1321819</td>
<td>1-Nov-01</td>
<td>active</td>
<td>47</td>
</tr>
<tr>
<td>ISSA</td>
<td>Issaquah</td>
<td>197515</td>
<td>1342742</td>
<td>1-Nov-01</td>
<td>3-Feb-03</td>
<td>24</td>
</tr>
</tbody>
</table>

†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.
4.2.2  Tributary Inflow

In addition to long-term gauging records for Issaquah Creek (USGS 12121600), the U.S. Geological Survey (USGS) and King County have gauged the flows of a number of small tributaries to Lake Sammamish (Table 3, Figure 6). However, with the exception of Issaquah Creek, the records for these tributaries are of limited duration and do not cover the selected model calibration period. King County has recently developed basin hydrologic models for the entire Lake Sammamish watershed as part of the Freshwater program. Sixteen separate models representing 14 specific inflow streams and runoff from 2 eastern nearshore areas not necessarily represented by a discrete channel were developed for the basin (King County in progress). Since modeled runoff from some basins represented overland and groundwater flow from nearshore land areas distributed around the perimeter of the lake, the delineated basin boundaries were used to define discrete inflow points from the modeled basins to the lake model (Figure 7). Although a watershed model of Issaquah Creek (WY 1988-2003) has been developed recently (King County in progress), observed discharge from the USGS gauge is used in the current version of the model. Use of modeled Issaquah flow is planned for use in the next version of the model. Total HSPF-modeled tributary discharge for the period 1995-2002 is shown in Figure 5.

The HSPF model versions used in the current Lake Sammamish CH3D-Z application were existing versions or created using 1995 land cover and default parameter assumptions and were not calibrated to more recent gauging data. West Consultants (2004) used the same Lake Sammamish tributary basin HSPF model output as described above to develop a long-term water balance of the lake. Based on their analysis, total flow volumes were over-estimated for Tibbetts (29 %) and Pine Lake (12 %) Creeks and under-estimated for Laughing Jacobs (45 %), Inglewood (44 %) and Lewis (8 %) Creeks. West Consultants (2004) used these comparisons to derive scaling factors for the HSPF model output to better represent long-term flow volumes in their lake water balance. An approach similar to this and/or further testing and refinement of the HSPF models will be considered in future lake model development efforts.

4.2.3  Lake Water Surface Elevations

Daily water surface elevation records in feet are available from the USGS Vasa Park gauge (USGS 12122000) for the period 1939-2003 (see Figure 6). The vertical datum for these lake stage records is NGVD 1929. The data for the selected model calibration period were converted to model datum in feet by subtracting the normal pool elevation (26.51 ft NGVD 1929) from the reported water levels. Daily stage records for the period 1995-2002 are shown in Figure 5.
## Table 3. Selected stream gauges in the Sammamish basin.

<table>
<thead>
<tr>
<th>Site Code</th>
<th>Site Name</th>
<th>Northing</th>
<th>Easting</th>
<th>Date Installed</th>
<th>Date Removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>King County</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>02a</td>
<td>Bear Creek @ Mouth</td>
<td>248836</td>
<td>1326557</td>
<td>10/1/1987</td>
<td>Active</td>
</tr>
<tr>
<td>15b</td>
<td>Pine Lake Creek at E Lake Sammamish Pkwy</td>
<td>221716</td>
<td>1332721</td>
<td>10/1/1999</td>
<td>Active</td>
</tr>
<tr>
<td>15c</td>
<td>Laughing Jacobs Creek at E Lake Sammamish Pkwy</td>
<td>208616</td>
<td>1339535</td>
<td>7/1/1991</td>
<td>Active</td>
</tr>
<tr>
<td>15g</td>
<td>George Davis Creek</td>
<td>226785</td>
<td>1336241</td>
<td>7/1/1999</td>
<td>Active</td>
</tr>
<tr>
<td>51m</td>
<td>Sammamish River @ Marymoor Weir</td>
<td>242764</td>
<td>1323957</td>
<td>7/18/2001</td>
<td>Active</td>
</tr>
<tr>
<td>63a</td>
<td>Lewis Creek at West Lake Sammamish Parkway SE</td>
<td>208198</td>
<td>1329022</td>
<td>1/1/1998</td>
<td>Active</td>
</tr>
<tr>
<td>67a</td>
<td>Tibbetts Creek above Tributary 0170</td>
<td>204163</td>
<td>1335573</td>
<td>10/1/1987</td>
<td>9/1/1991</td>
</tr>
<tr>
<td>USGS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12121600</td>
<td>Issaquah Creek near mouth</td>
<td>203838</td>
<td>1340505</td>
<td>10/1/1963</td>
<td>Active</td>
</tr>
<tr>
<td>12121700</td>
<td>Tibbetts Creek near Issaquah</td>
<td>199951</td>
<td>1336395</td>
<td>9/1/1963</td>
<td>12/1/1976</td>
</tr>
<tr>
<td>12121720</td>
<td>Laughing Jacobs Creek</td>
<td>208718</td>
<td>1339485</td>
<td>10/1/1986</td>
<td>9/30/1988</td>
</tr>
<tr>
<td>12121815</td>
<td>Pine Lake Creek at BNRR</td>
<td>222096</td>
<td>1333048</td>
<td>6/26/1987</td>
<td>9/30/1988</td>
</tr>
<tr>
<td>12121830</td>
<td>Inglewood Creek at E Lk Samm Pkwy</td>
<td>226913</td>
<td>1336004</td>
<td>10/1/1986</td>
<td>9/30/1988</td>
</tr>
<tr>
<td>12122000</td>
<td>Lake Sammamish at Vasa Park</td>
<td>214022</td>
<td>1324895</td>
<td>1/30/1939</td>
<td>Active</td>
</tr>
<tr>
<td>12124500</td>
<td>Bear Creek at Redmond</td>
<td>246735</td>
<td>1325986</td>
<td>6/1/1945</td>
<td>3/23/1987</td>
</tr>
<tr>
<td>12125200</td>
<td>Sammamish River near Woodinville</td>
<td>259536</td>
<td>1318058</td>
<td>2/1/1965</td>
<td>Active</td>
</tr>
</tbody>
</table>

Figure 5. Daily total precipitation at Sea-Tac (A), observed Issaquah Creek discharge, HSPF-modeled runoff from remaining tributary basins, and lake stage (B), and comparison of the total gauges and HSPF-modeled discharge to the distributed flow required to balance the water budget (C).
Figure 6  Selected King County and USGS stream and stage gauging locations.
Figure 7  Tributary discharge and nearshore basin runoff assignments to the CH3D-Z model grid.

4.2.4  Lake Discharge

Since 1964, discharge from the lake has been controlled by a broad-crested weir. In July 1998 the weir was modified and a low-flow notch was 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 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 ungauged runoff between the lake weir and the Woodinville gauge. Ungauged runoff was estimated as 10 percent of observed Big Bear Creek discharge. The formula used to estimate lake outflow was:

\[ Q_{\text{lake outflow}} = Q_{\text{Woodinville}} - 1.1 Q_{\text{BigBear}} \]

Another possible approach was the use of available stage-discharge relationships developed for the weir (Figure 8). However, during the process of developing the CH3D-Z model, a hydraulic modeling study confirmed previous suggestions (Hartley 1997) that Lake Sammamish stage could be affected by backwater conditions resulting from high flow (and stage) at the mouth of
Figure 8  Selected stage-discharge relationships for outflow over the Lake Sammamish weir.

Big Bear Creek (West Consultants 2004). The change in daily lake stage resulting from the January 1997 rainfall event illustrates that the lake stage-discharge relationship can have a different relationship during the rising and falling limb of the hydrograph (Figure 9). Therefore, a discharge based on a fixed stage-discharge relationship will over-estimate discharge rates during large storms.

Figure 9  Example of lake outlet stage-discharge hysteresis resulting from New Years 1997 storm.
Figure 10A compares the lake outlet flow rates derived using gauging data and the formula given above and flow rates derived from available stage-discharge relationships for the period before and after the July 1998 weir modification. Available weir (51m) 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 10B). A comparison of the cumulative discharge for the period 1995-2002 (see Figure 10C) 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.

The next version of the model will have the capability to predict lake outflow from a give stage-discharge relationship, although the stage-discharge hysteresis noted above will not be accounted for in that version. Another possibility 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. Testing of this approach is planned in the future.

4.2.5 Water Balance

Based on the available gauged Issaquah Creek and HSPF-modeled tributary flows, Sea-Tac precipitation, ACOE evaporation rates, and gauged lake water surface elevations, a water balance approach was used to estimate the daily amount of water (addition or removal) that would be required to balance the water budget \( (Q_{\text{distributed}}) \). The water budget equation took the form:

\[
Q_{\text{distributed}} = (Q_{\text{Issaquah}} + Q_{\text{HSPF}} + Q_{\text{rainfall}}) - (Q_{\text{evaporation}} + Q_{\text{outflow}} + Q_{\text{storage}})
\]

The calculated distributed inflow conceptually accounts for unaccounted groundwater inflows and outflows to the lake since all surface water inputs are explicitly accounted for. However, the distributed inflow estimate also includes errors propagated from errors in the other flow estimates (gauged and modeled with HSPF). The largest errors are associated with the calculated storage based on observed changes in water surface elevation. For example, an error of 1 cm in the measured water surface elevation translates to an error of about 80 cfs. A similar problem was encountered by WEST Consultants (2004) in developing a water balance for the lake. They identified the same difficulties (i.e., errors in the observed water surface elevation and tributary flow estimates) and suggested using a numerical filtering technique to smooth the water surface elevation fluctuations and improve the HSPF accuracy in predicting the timing and magnitude of modeled tributary inputs.

The calculated distributed flow required to balance the water budget was added as a lateral (i.e., distributed) inflow along the eastern shoreline in the CH3D-Z model. The resulting match between modeled and observed water surface elevation for the model calibration period is shown in Figure 11. The annual average flow associated with each water budget component and the relative contribution of each inflow are presented in Figure 12.
Figure 10  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.
Figure 11  Comparison of model-predicted and observed daily Lake Sammamish stage, 1995-2002.
Figure 12  Annual average flow contribution from each component of the water budget described in the text (A) and the relative contribution of each inflow component (B).
4.3 Water Quality Data

4.3.1 Tributary Water Temperatures

The water quality (including temperature) of 8 Lake Sammamish tributaries, including Issaquah Creek has been monitored by King County on a routine basis\(^1\) during the period selected for model calibration (Table 4, Figure 13). Continuous (15 minute) temperature data collection on Issaquah Creek began in August 2001. The current version of the model uses linear interpolation of the routine temperature data to create a daily time series for each monitored tributary. Observed temperature time series are assigned to nearby tributaries that are not currently monitored (Table 5). Figure 14 presents the temperature data for the routinely monitored streams. Figure 15 presents a comparison between recent continuous temperature records and routine monitoring data for Issaquah Creek.

4.3.2 In-lake Temperature Profiles

Profiles of temperature (and a suite of additional water quality parameters) of 6 in-lake stations has been conducted on a routine basis\(^2\) during the period selected for model calibration (Table 6, Figure 16). These data, and data from a surface grab sample at the outlet of the lake, have been used to evaluate the performance of the model during the years selected for model calibration. Temperature profile plots from all six stations for selected sampling events representing March, June, September, and December 2002 are shown in Figure 17. All 2002 temperature profile plots for the central Lake Sammamish monitoring station (0612) are shown in Figure 18. Near-surface temperatures recorded at the lake outlet (0625) and just downstream of the Lake Sammamish weir (0486) are shown in Figure 19.

Two RUSS buoys were deployed in Lake Sammamish in 2001. These buoys were designed to conduct temperature, dissolved oxygen, pH, specific conductance, and algal fluorescence profiling at a frequency of up to four times per day during the summer (see Figure 16 for their locations). Profiling during winter was less frequent due to limitations imposed by the power supplied from solar panels on the buoy. Due to technical difficulties and vandalism, there are data gaps and some of the data are of questionable quality – although temperature measurements have been the least problematic (Figures 20 and 21). When the temperature data have been reviewed and suspect data identified and censored from the data set, these data will also be used to evaluate model performance.

---

\(^1\) Monthly grab samples with up to 6 additional wet season and 6 additional dry season grab storm water samples per year (King County 2002).