Quality Assurance Project Plan

Lake Whatcom TMDL Study

by
Robert F. Cusimano, Steve Hood, Jing Liu

Washington State Department of Ecology
Environmental Assessment Program
Olympia, Washington 98504-7710

July 2002

This report is available on the Department of Ecology home page on the World Wide Web at http://www.ecy.wa.gov/biblio/0203074.html.

Quality Assurance Project Plan

Lake Whatcom TMDL Study

July 2002

303(d) listings addressed in this study:
Lake Whatcom (WA-01-9170) – Dissolved Oxygen
Silver Beach Creek (WA-01-3120) – Fecal Coliform

Ecology EIM Number: WHATCOM

Approvals

Approved by:	July 11, 2002
Steven L. Hood, Bellingham Field Office	Date
Approved by:	July 15, 2002
Richard M. Grout, Manager, Bellingham Field Office	Date
Approved by:	July 6, 2002
Karol Erickson, Unit Supervisor, Watershed Ecology Section	Date
Approved by:	July 11, 2002
Bob Cusimano, Watershed Ecology Section	Date
Approved by:	July 11, 2002
Will Kendra, Section Manager, Watershed Ecology Section	Date
Approved by:	July 11, 2002
Stuart Magoon, Director, Manchester Environmental Laboratory	Date
Approved by:	July 11, 2002
Cliff Kirchmer, Ecology Quality Assurance Officer	Date

Table of Contents

List of Figures

List of Tables

Project Description

Problem Statement

The Clean Water Act (1972), Section 303(d), requires that states report waterbodies that do not meet ambient water quality standards. The resulting inventory of impaired water bodies is called the 303(d) list. Waterbodies on the list are slated for Total Maximum Daily Loads (TMDLs), which are assessments of the pollutant loading capacity of a waterbody that can be met and still allow the waterbody to meet the assigned water quality criteria and support for beneficial uses.

Lake Whatcom is listed on the Washington State 303(d) list of waterbodies not attaining water quality criterion for dissolved oxygen. Lake Whatcom has historically exhibited oxygen depletion in the bottom waters (hypolimnion) of Basin 1 and Basin 2 (URS, 1985; Walker, Matthews, and Matthews, 1992; Matthews and Matthews, 1993, 1994, 1995; Matthews, Hilles, and Matthews, 1996, 1997, 1998; Matthews, Hilles, Vandersypen, Mitchell, and Matthews, 2001). Washington State Department of Ecology (Ecology) examined the rate of oxygen depletion in the hypolimnion for the June through August periods of stratification for 1983-97 and found that the oxygen depletion rates were significantly increasing during this period (Pelletier, 1998). Hypolimnetic dissolved oxygen concentrations have also been shown to be decreasing in Basin 1 and 2 (Matthews, Hilles, Vandersypen, Mitchell, and Matthews, 2001). In recent years, Basin 2 has had higher concentrations of hydrogen sulfide, ammonia, and iron and greater denitrification (conversion of nitrate to nitrogen and nitrous oxide gas by bacteria), which suggest that Basin 2 is experiencing anoxic conditions like Basin 1 and may be getting worse (Matthews, Hilles, Vandersypen, Mitchell, and Matthews, 2001).

Low dissolved oxygen in the hypolimnion of Lake Whatcom is partly caused by the direct loading of organic matter from the watershed. Dissolved oxygen is consumed as bacteria decompose the organic matter in the water column and as it settles and becomes part of the bottom sediments. During the summer and fall, oxygen can become depleted in the hypolimnion because the transfer of oxygen from the atmosphere to the bottom waters is limited by thermal stratification. Stratification occurs when the surface water (epilimnion) is heated and becomes thermally separated from the deeper, cooler water in the hypolimnion (i.e., the bottom water does not mix with the well oxygenated surface water of the epilimnion).

Low dissolved oxygen in the lake is also partly caused by eutrophication processes that are driven by the availability of nutrients like phosphorus and nitrogen, and the physical conditions present in the lake during the summer and fall (e.g., warm surface temperatures and abundant sun light). In the case of Lake Whatcom, the limiting nutrient that controls algal productivity is primarily phosphorus (URS, 1985). However, during late summer and early fall, Basin 1 may be co-limited by nitrogen (Mathews, Hilles, and Pelletier, 2002). Additions of phosphorus can lead to greater production of algae. As the algae die, they become part of the organic matter in the water column and sediments and dissolved oxygen is consumed as the dead algae are decomposed by bacteria. When the hypolimnion has very low or no dissolved oxygen (anoxic conditions) at the lowest depths, the sediment releases phosphorus into the water column which can stimulate additional algal growth leading to even more decomposition and associated oxygen consumption.

Less oxygen in the hypolimnion is also undesirable because it limits the available habitat for oxygen consuming organisms like fish. In addition, anoxic conditions may require greater treatment of the water before it can be used as a drinking supply, because depletion of dissolved oxygen in the bottom waters can facilitate the movement of some metals like iron into the water column from the sediments and increase turbidity. Anoxic conditions can also increase the formation of hydrogen sulfide which is toxic to fish and has an undesirable rotten-egg smell that makes the water less aesthetically pleasing and drinkable. A particular concern in Lake Whatcom is that anoxic conditions may increase the bioaccumulation of mercury in fish by providing conditions that favor the methylation of inorganic mercury (changing mercury into the toxic form) in the sediments by bacteria (i.e., anaerobic bacteria that derive oxygen from sulfate for the oxidation of organic matter).

Algae and algal byproducts can also cause degradation in the quality of the drinking water supplied from the lake. Increases in algae can lead to taste and odor issues that are not removed through treatment. Another result of increased algal growth on the use of Lake Whatcom as a drinking water source is the potential increase in disinfection by-products. The primary class of harmful disinfection by-products is trihalomethanes. Trihalomethanes are created when the chlorine used to disinfect the water combines with organic carbon in the source water. Increases in algal growth provide higher levels of organic carbon leading to higher levels of trihalomethanes. Over the last four years, the levels of trihalomethanes in the city of Bellingham (COB) finished water have increased significantly, especially in the fall (Mathews et al., 2002).

Among the tributaries/drainages of the Lake Whatcom watershed, Silver Beach was listed on the 303(d) list of waterbodies not attaining water quality standards for bacteria. In addition, Austin Creek, Park Place Drain, and Cable Street drainage were all recommended for listing as impaired by Ecology for not attaining water quality criteria for bacteria. The water quality of these tributaries/drainages will be included as part of the Lake Whatcom TMDL study and the bacteria listings addressed.

Overall, Ecology's Northwest Regional Office (NWRO) is concerned about pollutant loading adversely affecting the beneficial uses of Lake Whatcom. NWRO is particularly concerned about Lake Whatcom because the lake is the drinking water supply for the COB and some residents that live near the lake. The NWRO concerns and the listing of Lake Whatcom as impaired for low dissolved oxygen triggered this TMDL study.

It has also been recommended that Lake Whatcom be placed on the 303(d) list for impairments resulting from the toxic pollutants PCB-1254, PCB-1260 (Serdar 1999) and mercury (Serdar 2001) at the next listing cycle. The study to address those impairments will be addressed by a separate Quality Assurance (QA) Project Plan.

Study Area

Figure 1 shows the location of Lake Whatcom and the general study area. Lake Whatcom is a large, deep and monomictic natural lake located in Whatcom County, Washington. Part of the Lake Whatcom watershed also lies in Skagit County. The lake consists of three distinct lake basins, separated by two glacial sills from north to south, and 22 drainages as shown in Figure 2.

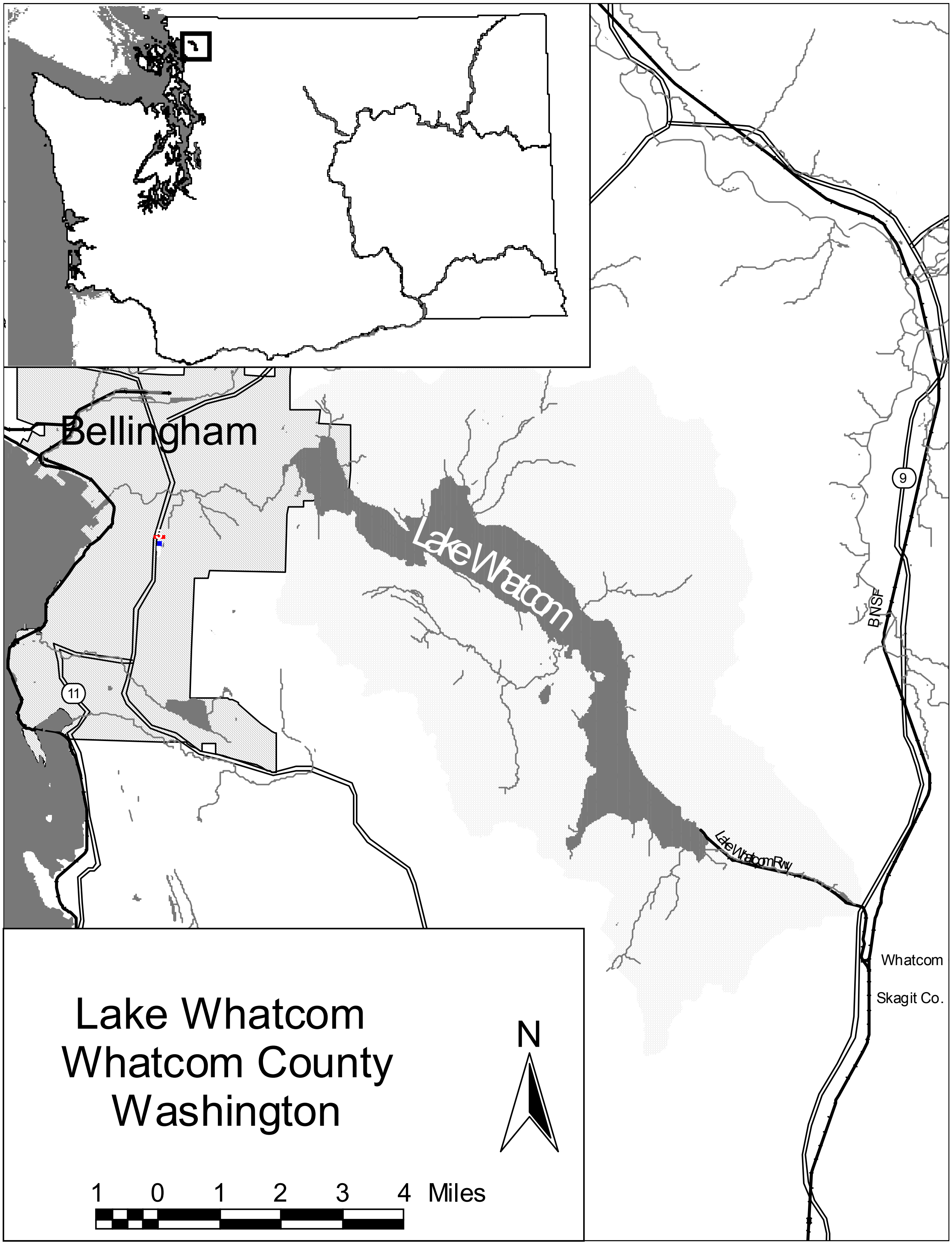


Figure 1. Lake Whatcom Vicinity.

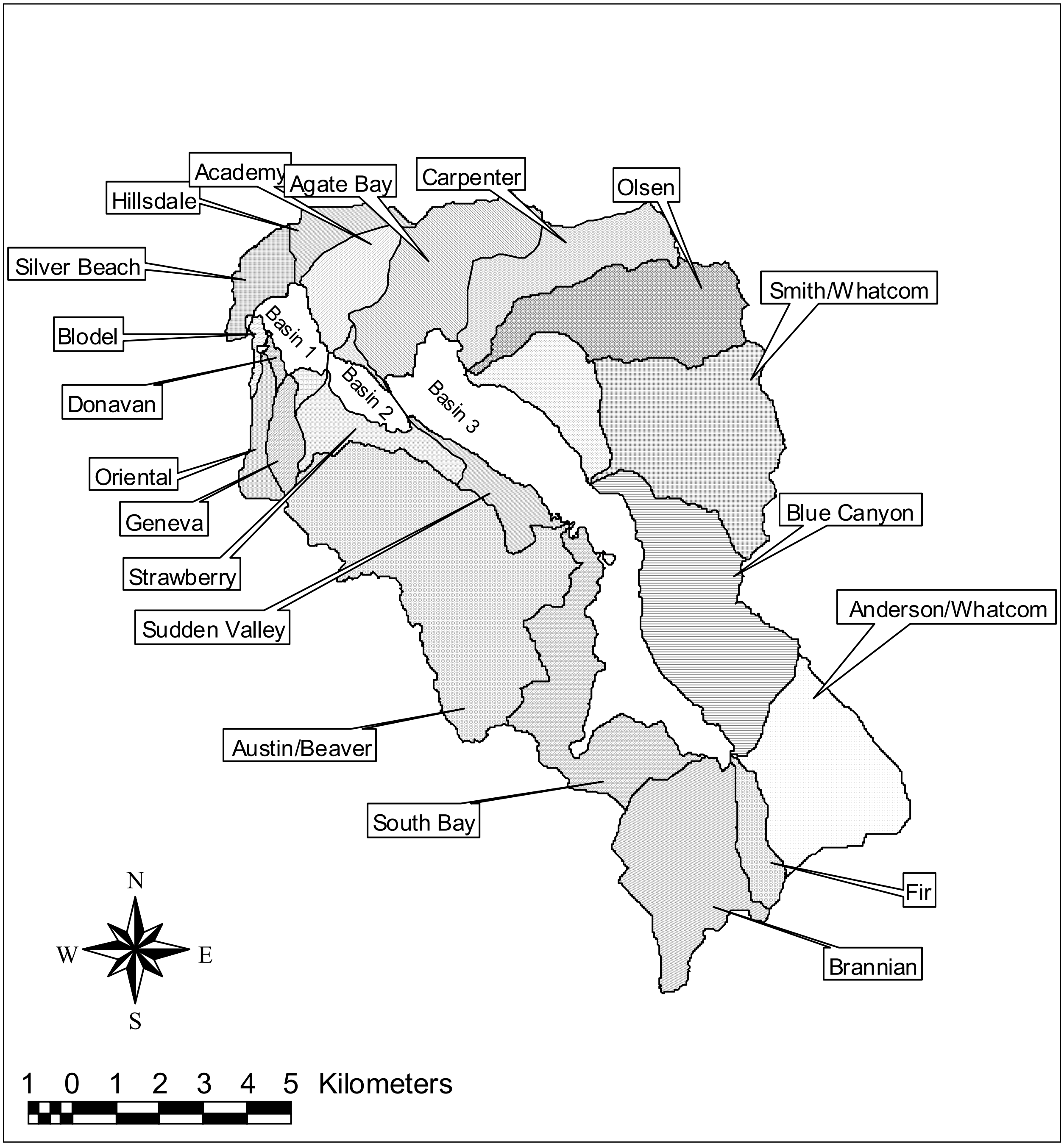


Figure 2. Lake Whatcom Basins and Dainages.

The morphological characteristics of each lake basin are summarized in Table 1 (Lighthart et al., 1972). Basin 1 is located at the north end of the lake within the city limits of Bellingham, and it is separated from Basin 2 by Geneva sill, which is 3-5 m below the surface. Basin 2 and Basin 3 are mainly located within the boundary of Whatcom County, and the two basins are separated by Strawberry sill, which is 10-15 m below surface. Basin 3 is the largest; it contains about 96 percent of the total volume of the lake with a maximum depth of 103 m. Basins 1 and 2 are small and shallow, with a mean depth of 9.2 and 11.2 m respectively. More recent detailed data on Lake Whatcom Bathymetry from the United States Board of Reclamation Survey of 2000 has been made available and will be used in this study.

Table 1. Lake Whatcom Morphometric Data.

	Basin 1	***Basin 2***	***Basin 3***	***Entire Lake***
Volume ($m^3 \times 10^6$)	19.4	18.0	883.5	921
% of Lake Volume	2.1	2.0	95.9	100.0
Maximum Depth (m)	29	21	103	103
Mean Depth (m)	9.2	11.2	54	46
Surface Area (km^2)	2.1	1.6	16.6	20.3
Length (km)	2.2	2.5	13.3	19.2
Maximum Width (km)	1.1	1.0	1.7	1.7

All of the major tributaries and many of the intermittent tributaries in the watershed flow into Basin 3, which receives 87 percent of the drainage from the watershed. The remaining watershed areas are drained by intermittently flowing streams, surface runoff directly into the lake, or man-made drainage systems (Delahunt, 1990). Seven perennial tributaries flow into Lake Whatcom; they are Anderson, Smith, Olsen, Carpenter, Austin, Brannian, and Fir creeks. Among them, Anderson, Austin, and Smith Creeks are the largest.

Most of the Lake Whatcom Watershed is forested. Open water covers 13% of the watershed. Table 2 shows land use by drainage area for the drainage basins defined by the Water Resources Inventory Area 1 (WRIA 1) Watershed Management Project. The drainage areas are mapped in Figure 2. The predominant land use in the upper portion of the watershed is different from that in the mid to lower portions. Basin 3 is primarily forestry, and Basins 1 and 2 are primarily urban and residential. Human impacts in the watershed are mainly from urbanization, primarily associated with residential development in Basins 1 and 2. The existing population within the watershed is about 13,000 based on the 2000 census. Current zoning will allow an increase of up to about 28,000 residents within the watershed (Hisch Consulting Services, 1998). The increased development and population growth in the watershed will likely have some impact on lake water quality.

Table 2. Land Use by Drainage.

Drainage Name	Acres	Water/Wetland	Developed	Bare	Forest	Grass/Shrub/Ag
Academy	894	1.1%	9.0%	0.4%	85.5%	4.1%
Agate Bay	2129	0.5%	2.7%	0.4%	88.6%	7.8%
Anderson/Whatcom	2611	0.8%	0.1%	0.9%	94.3%	4.0%
Austin/Beaver	5363	0.5%	3.6%	1.3%	94.4%	0.3%
Blodel	96	1.2%	59.6%	0.5%	36.0%	2.8%
Blue Canyon	3308	1.3%	0.0%	0.4%	95.4%	2.8%
Brannian	2552	0.1%	0.1%	4.9%	94.5%	0.3%
Cable	106	0.8%	56.3%	1.7%	33.7%	7.5%
Carpenter	1659	0.3%	1.2%	0.7%	93.2%	4.5%
Donavan	70	0.0%	61.0%	0.0%	38.1%	1.0%
Eagle Ridge	91	6.8%	27.8%	0.0%	56.6%	8.8%
Fir	544	0.4%	0.0%	8.9%	89.3%	1.3%
Geneva	386	0.0%	12.2%	5.2%	82.3%	0.2%
Hillsdale	522	0.0%	21.2%	0.0%	74.0%	4.8%
North Shore	1167	2.1%	5.7%	0.0%	82.8%	9.3%
Olsen	2433	0.0%	0.2%	0.4%	99.1%	0.4%
Oriental	405	0.0%	13.0%	1.3%	85.2%	0.5%
Silver Beach	524	0.6%	48.4%	0.0%	48.5%	2.5%
Smith/Whatcom	3301	0.0%	0.0%	1.2%	97.6%	1.2%
South Bay	2316	0.3%	3.5%	2.4%	93.1%	0.7%
Strawberry	774	0.5%	14.6%	1.3%	83.3%	0.3%
Sudden Valley	599	0.4%	24.1%	0.0%	74.7%	0.7%

A pipeline was constructed by COB in 1962 to divert water from the Middle Fork of the Nooksack River to Lake Whatcom via Mirror Lake and Anderson Creek at the south end of Basin 3. The diversion operates during the fall and winter when the Lake is below 312 feet above mean sea level, and operates continuously during the spring and summer when sufficient water is available in the Middle Fork. During the summer, it is often the major water source for the lake. Historically, the diversion was closed in order to prevent potential flooding only when the lake level was high and precipitation was likely. Since 1998, the city has voluntarily decreased its diversion during low flow periods to help maintain in-stream flows in the Middle Fork of the Nooksack River and protect salmon.

Whatcom Creek, located at the north end of Basin 1, is the only natural outlet of Lake Whatcom. It drains to Bellingham Bay. The outlet flow and the lake level are regulated by a manually controlled dam, which was constructed in 1938 by COB (URS, 1985). The city operates the dam in order to provide additional water storage and prevent flooding. Flow into Whatcom Creek can be reduced if water supply is low.

The lake is a critical water resource for WRIA1. Since the 1880s, it has served as a water supply source, and now it is the critical water source for approximately 86,000 Whatcom County residents, including COB and Whatcom County Water District No. 10. The number of direct withdrawals by single family residencies is not known but is estimated to be from 150 to 250. Whatcom Falls Hatchery also withdraws water from the lake in Basin 1. The city's intake is about 12 m deep and is located about 366 m offshore in Basin 2. The district's intake is located in a protected cove of Basin 3 at a depth of 21 m.

Like most temperate lakes, weather conditions determine the timing of stratification in Lake Whatcom (Matthews, R. A. et al., 2001). Current and historical data show that stratification can occur as early as in April or May at all sites except the water intake, which is too shallow to develop a stable stratification. Stratification often develops gradually; it may not be stable until June and it could last until fall or winter. Timing of destratification varies from basin to basin. The two shallow basins, Basins 1 and 2, cool very quickly and can destratify by late October or early November. However, Basin 3 usually cools slowly and destratification may not occur until December due to its large volume.

The patterns of water movement in the lake are very complex because of the three interacting basins separated by glacial sills. Results from previous studies showed that the water movement could occur in both directions across the sills of the lake, which depends on wind and temperature conditions in the lake (Western Washington State College, 1970). Generally, the flow direction is from Basin 3 to Basin 2, to either the municipal withdrawal or basin 1, and then to Whatcom Creek. However, subsurface currents appear to move water in the opposite direction when the wind is blowing upstream.

Beneficial Uses and Water Quality Criteria

Lake Whatcom provides source water for drinking water supply and screened and chlorinated industrial water to the COB through an intake in Basin 2. Water District 10 withdraws source water for the drinking water supply from Basin 3. Many homeowners also draw source water directly from the lake in both Basin 2 and 3. Washington State Department of Fish and Wildlife withdraws water from Basin 1 (near Mill Wheel Creek) to supply water to the Whatcom Falls Fish Hatchery.

Lake Whatcom provides habitat to both warm and cold water fish. The lake provides the brood stock for the Brannian Creek Hatchery, which is the state's source of kokanee for plants throughout the state. The bass fishing tournaments in Lake Whatcom attract fishers from all of Western Washington.

Lake Whatcom is also a regional recreation destination for swimming and water skiing. Many homes have docks with water craft moored to them throughout the summer months.

The water quality standards as outlined in Chapter 173-201A of the Washington Administrative Code include designated beneficial uses established for each classification, criteria that are both numeric and narrative, and an anti-degradation policy. Lake Whatcom is classified as Lake Class and its tributaries are Class AA (extraordinary).

The water quality of Lake Whatcom should meet or exceed the requirements for all substantial uses including water supply, salmonid rearing, wildlife habitat, and recreation. The lakes and tributaries should markedly and uniformly exceed the requirements for all or substantially all uses.

Water quality standards establish beneficial uses of waters and incorporate specific criteria for parameters such as dissolved oxygen and fecal coliform densities. The criteria are intended to define the level of protection necessary to support the beneficial uses. The dissolved oxygen criterion for Lake Whatcom is “no measurable change from natural conditions”; however, in other TMDLs, Ecology and EPA have allowed a 0.2 mg/L degradation in dissolved oxygen concentration due to human impacts.

We will apply the Lake Class dissolved oxygen criteria "No measurable decrease from natural conditions" to Lake Whatcom as follows:

Allow no more than a 0.2 mg/L deficit in dissolved oxygen from "natural conditions" at any point in the water column. Natural conditions for Lake Whatcom will be defined as the water quality conditions estimated by the calibrated CEQUALW2 model that would occur with no water diversions or water withdrawals, and the lake water level based on outlet dam operations under design-year conditions. Design-year conditions will be an estimated hydrologic year that provides critical low flow conditions equal to approximately a 10 percent recurrence frequency. In addition, loading to the lake from all subbasins will be equal to the estimated flows for each subbasin and the water quality constituent concentrations currently found in the creeks that represent the least disturbed watersheds.

The Class AA freshwater numeric criteria for fecal coliform:

> Fecal coliform organism levels shall both not exceed a geometric mean value of 50 colonies/100 ml, and not have more than 10 percent of all samples obtained for calculating the geometric mean value exceeding 100 colonies/100 ml (WAC 173-201A-030(1)(c)(A)).

Water quality criteria for bacteria are currently under revision. Ecology is proposing to replace fecal coliform with *E. coli* as the freshwater bacteria indicator to protect beneficial uses. The proposed freshwater numeric criterion for *E. coli* would be set at a concentration of 100 colonies/100 ml as a geometric mean.

Historical Data Review

Water Budget and Hydrology

Lake water level has been recorded by COB for many years; Figure 3 shows the water level data from January 1994 to February 2002. The maximum water level recorded during this period was 95.90 m. Bureau of Reclamation conducted a hydrographic survey of the lake in 1999 near water surface elevation of 95.8 m, which was measured by COB. The Bureau of Reclamation identified the COB datum as 2.5 feet below the North American Vertical Datum of 1988. Figure 4 shows the relationship between elevation and volume based on their survey data. Although there are some flow gauges in the tributaries of Lake Whatcom, historical flow data are very limited because those gauges, except Smith and Austin Creeks, have either been abandoned for lack of operation funds or some physical reasons. For example, the Anderson Creek gauge was out of the water much of the time under extreme low flow conditions before 2000. The lack of historical flow data makes it impossible to provide quantitative flow estimates for the tributaries. In addition, it is not possible to accurately calibrate a water quality model of the lake without tributary flow data.

Whatcom Creek is the only natural outlet of Lake Whatcom. Figure 5 shows that it is the major hydrologic outflow of the lake during winter; Georgia Pacific and COB were the major withdrawals during low flow periods. During the winter, the relative contribution of the diversion was small because of the large amount of water input from surface runoff; but, during the summer, the diversion was often the major water source for COB. Figure 6 shows the amount of water diverted from Middle Fork to the lake in the past twelve years. The amount of diverted water was largely reduced after 1998. The withdrawal by Georgia Pacific was also reduced since 2000 due to reduced operation. However, currently it is unclear how these two major hydrologic changes could impact lake water quality.

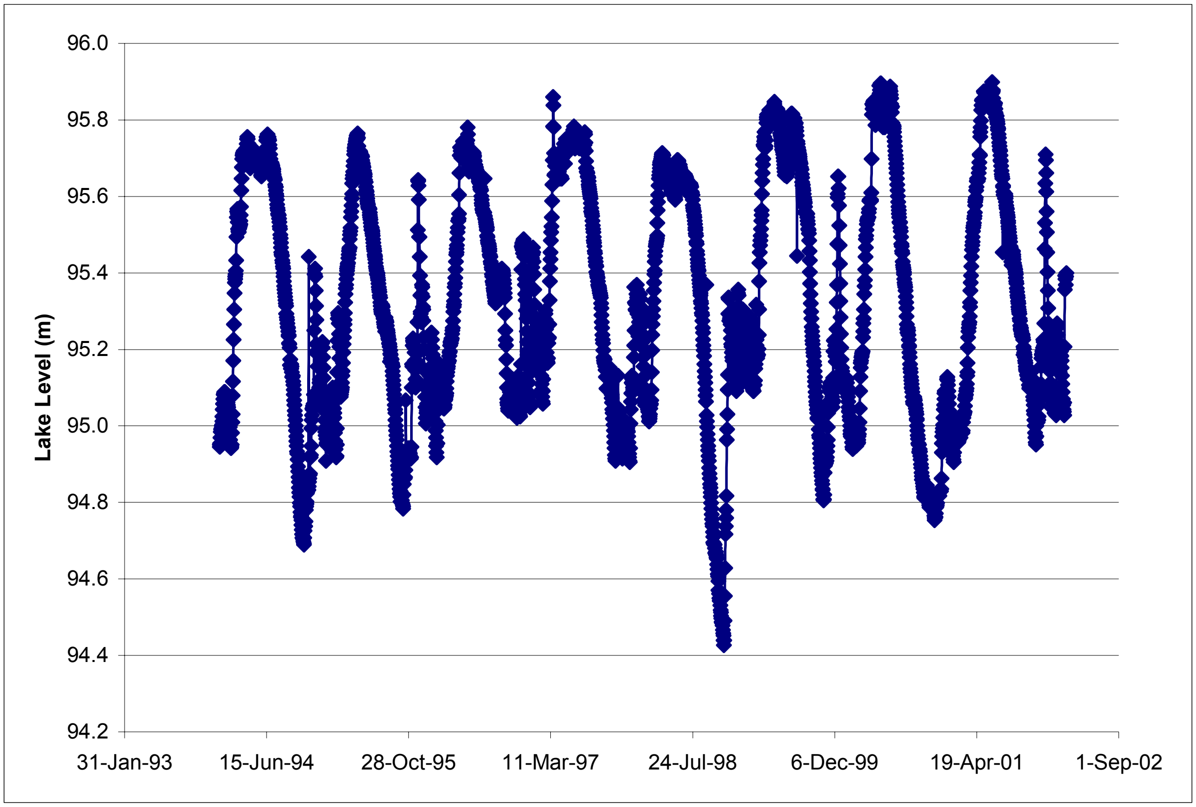


Figure 3. Historical Lake Whatcom Water Level (m).

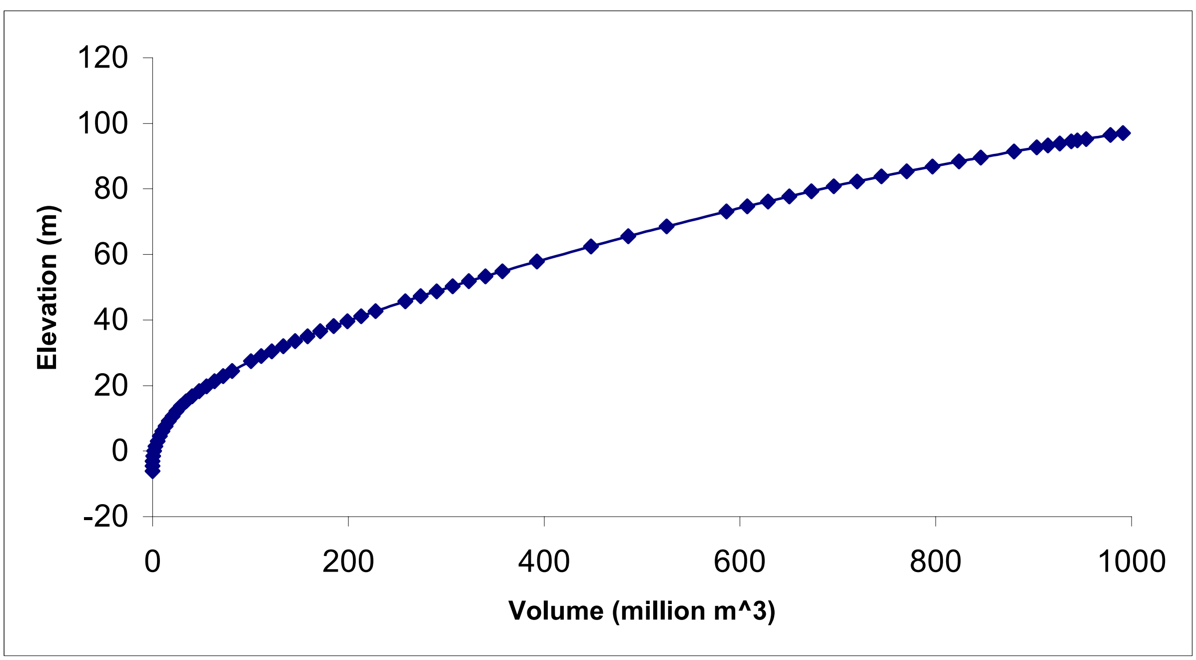


Figure 4. Elevation-Volume Data Analysis of Lake Whatcom.

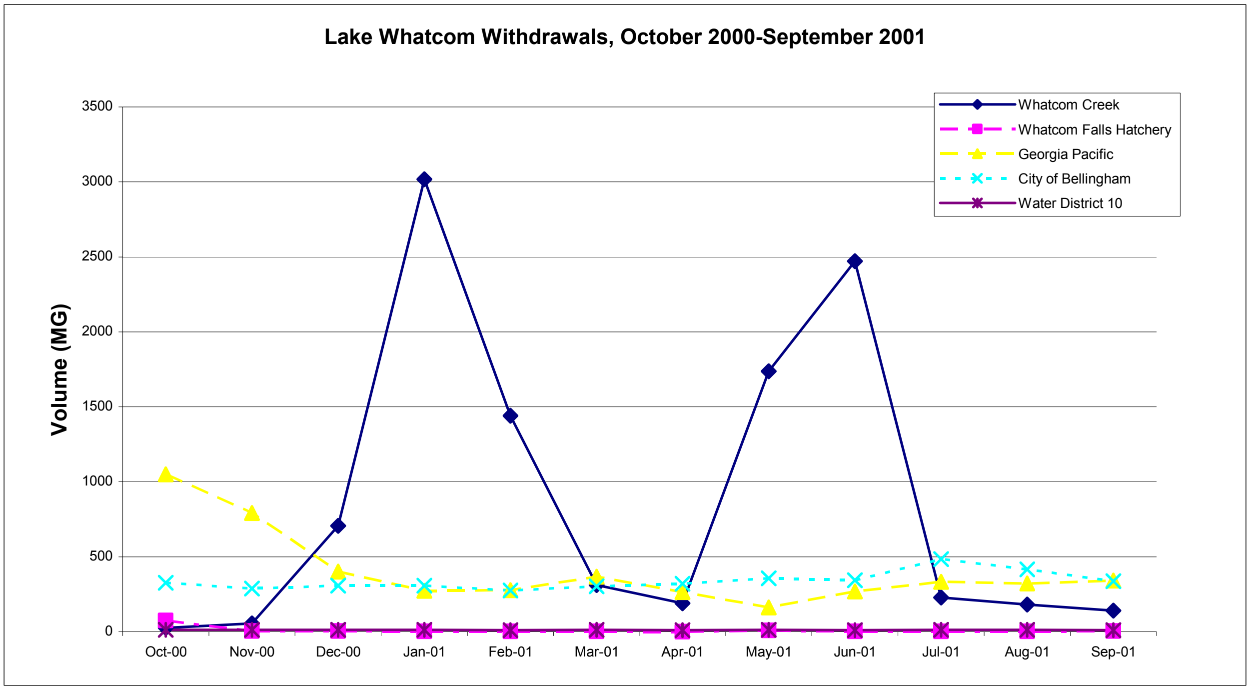


Figure 5. Lake Whatcom Monthly Hydrologic Withdrawals from October 2000 to September 2001.

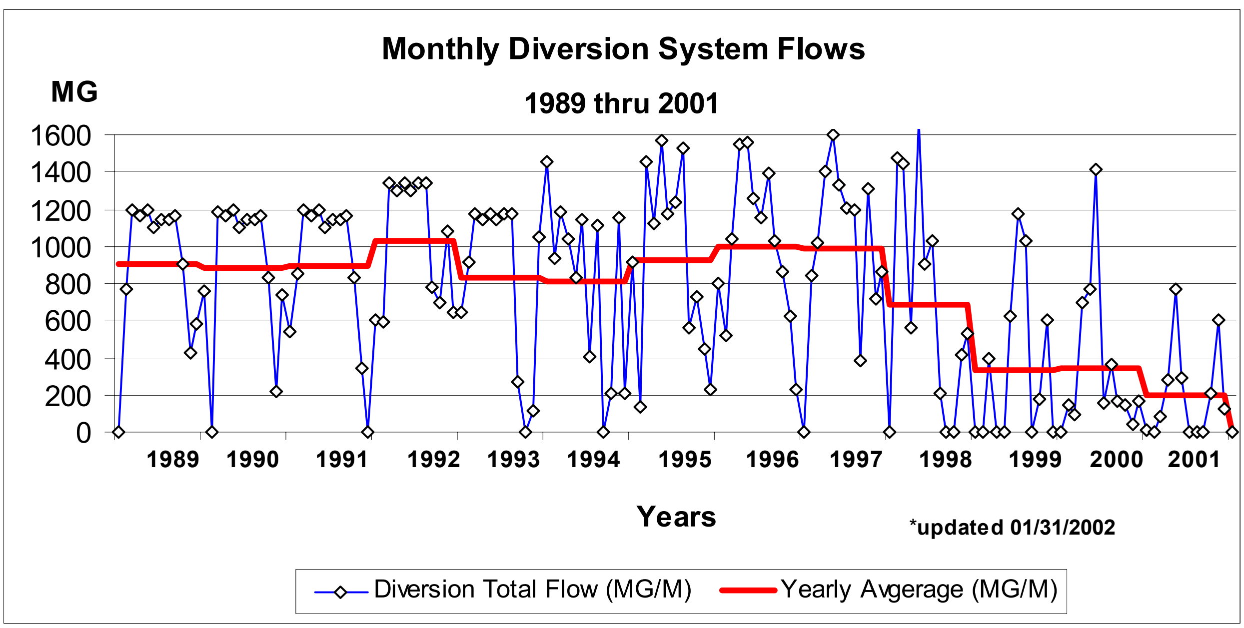


Figure 6. Middle Fork Nooksack River Diversion Data from 1989 to 2001.

A water balance model was developed by URS in 1985 to estimate the water budget in Lake Whatcom; however, the results of this model have some limitations because the land use data were outdated. Walker (1995) also estimated the water budget of the lake using the Hydrological Simulation Program – FORTRAN (HSPF) model. Like the URS study, the estimates obtained from this study have some limits too. The accuracy of the model was questionable due to lack of concurrent precipitation and stream flow data. In addition, the land use data were also outdated. Therefore, results from neither study can be used in the current project.

Matthews et al. (1998) developed a simple water balance model using the measured withdrawals from Lake Whatcom, Whatcom Creek outflow, COB withdrawal, Whatcom Falls Fish Hatchery, Georgia-Pacific Corporation, Water District No.10, Middle Fork diversion data, and the lake level data. The main objective of this model was to identify the lake's major water inputs and outputs, and meanwhile examine runoff and storage in the watershed. Like the Walker and URS studies, this effort was also limited by the lack of tributary stream flow data.

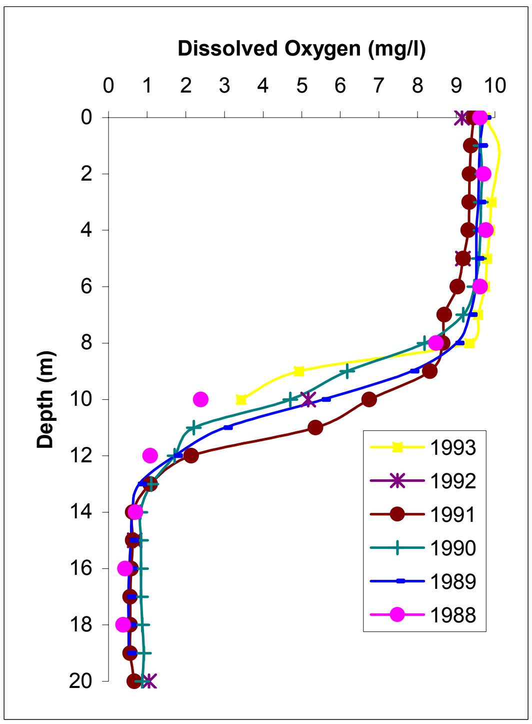
Currently, little information is available on the lake's internal hydrodynamics, which is believed to be very important in determining lake's physical and chemical properties. However, preliminary studies conducted by Western Washington University (WWU) suggested that water from the hypolimnion of Basin 1 can move into Basin 2 (Matthews et al., 2001). In addition, the study also showed that the diversion water from the Middle Fork was colder than the water in the epilimnion of the lake in summer when the lake is stratified. This may further complicate internal lake water movement. Matt Chase, a WWU geology graduate student, is studying the effects of Anderson Creek on Lake Whatcom hydrology as part of the research requirement for his M.S. thesis. The diversion was not operating in the summer of 2001 so his research is on hold. No information about groundwater inflow or outflow is available currently. This information is necessary in order to fully understand the hydrodynamics of the lake.

Water Quality

The Institute of Watershed Studies (IWS) at WWU and COB began conducting a monitoring program in Lake Whatcom and several of the lake's tributaries as early as the 1960s, and a long-term water quality monitoring program was initiated by the City and WWU in 1981 (Matthews et al., 1999). Therefore, a large amount of water quality data are currently available, which are the basis for the following analysis.

In these studies, water quality samples were collected at five long-term monitoring sites in Lake Whatcom (refer to Table 2 and Table 3 of Appendix A for site descriptions). The monitoring results showed that the lake stratifies during summer. pH and conductivity data showed only small differences among sites and depths except during the summer. The surface pH is higher in the summer due to increased photosynthetic activity, especially at Site 1. However, the hypolimnetic pH values decreased and conductivity values increased due to decomposition and the release of dissolved compounds from the sediments (i.e., anoxic conditions in the hypolimnion lead to decreased redox potential and the release of phosphorus, iron, and manganese from the sediments).

The left panel of Figure 7 shows the early September dissolved oxygen concentrations versus depth for the years 1988-1993 at Site 1; the right panel shows more recent data collected from 1994 to 2000. The graphs show that dissolved oxygen is stratified at Site 1. Plots of temperature and dissolved oxygen versus depth in Matthews et al. (1997, 1999, and 2000) indicate that there is a strong thermocline during the summer. Thermocline is defined as the plane or surface of maximum rate of decrease of temperature with respect of depth (Wetzel, 1983). The thermocline limits mixing, and thus oxygen transport between epilimnion and hypolimnion. Figure 7 also shows that dissolved oxygen concentrations are relatively uniform in both epilimnion and hypolimnion, except in the transitional layer, or metalimnion, which exists between the two, where the dissolved oxygen concentrations decrease rapidly. Additionally, this figure shows that the dissolved oxygen concentrations in the hypolimnion were decreasing in recent years at Site 1.



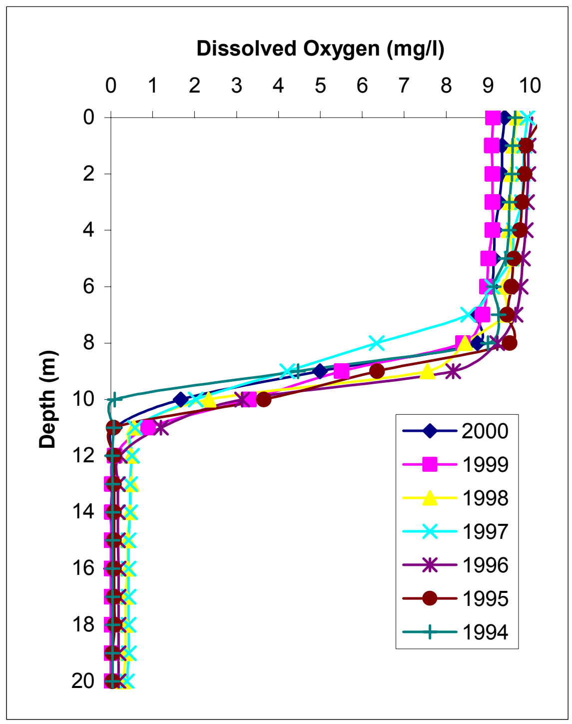


Figure 7. Dissolved Oxygen Concentrations Versus Depth for Lake Whatcom at Site 1 in Early September. Note: Data are Not Available at All Depths for the Year 1988, 1992, and 1993.

Sites 1 and 2 now develop severe hypolimnetic oxygen deficits during August and September, which may last until overturn in late October or early November, depending on weather conditions. The oxygen concentrations at the bottom of Site 1 were usually less than 1-2 mg/L during July, August, and September as far back as 1964. The analysis of current and historical lake oxygen data by Mathews et al. (2001) suggests that there is a decreasing trend in oxygen concentrations in Basin 1. The results of Pearson's correlation analyses of dissolved oxygen versus year showed statistically significant reductions in hypolimnetic oxygen levels at depths of more than 12 m from June to September at Site 1; however, no similar correlations were found between hypolimnetic temperatures or lake level versus hypolimnetic dissolved oxygen during this period. Therefore, the decreasing trend in dissolved oxygen is likely caused by some other reasons rather than increases in hypolimnetic temperatures or fluctuations in lake levels.

Pelletier's (1998) hypolimnetic oxygen deficit rate (HODR) analysis also suggests that there was a significant trend in decreasing oxygen levels in Basin 1 during the period of 1983 to 1997. If this trend in HODR continues, the lake might shift to a more eutrophic condition. Plot of volume-weighted dissolved oxygen concentrations in the hypolimnion of Site 1 versus year from 1988 to 2000 shows a decreasing trend in dissolved oxygen concentration (Figure 8). Volume-weighted averages are considered to be the most representative estimate of the mass of oxygen in the water column of a lake (Wetzel, 1983).

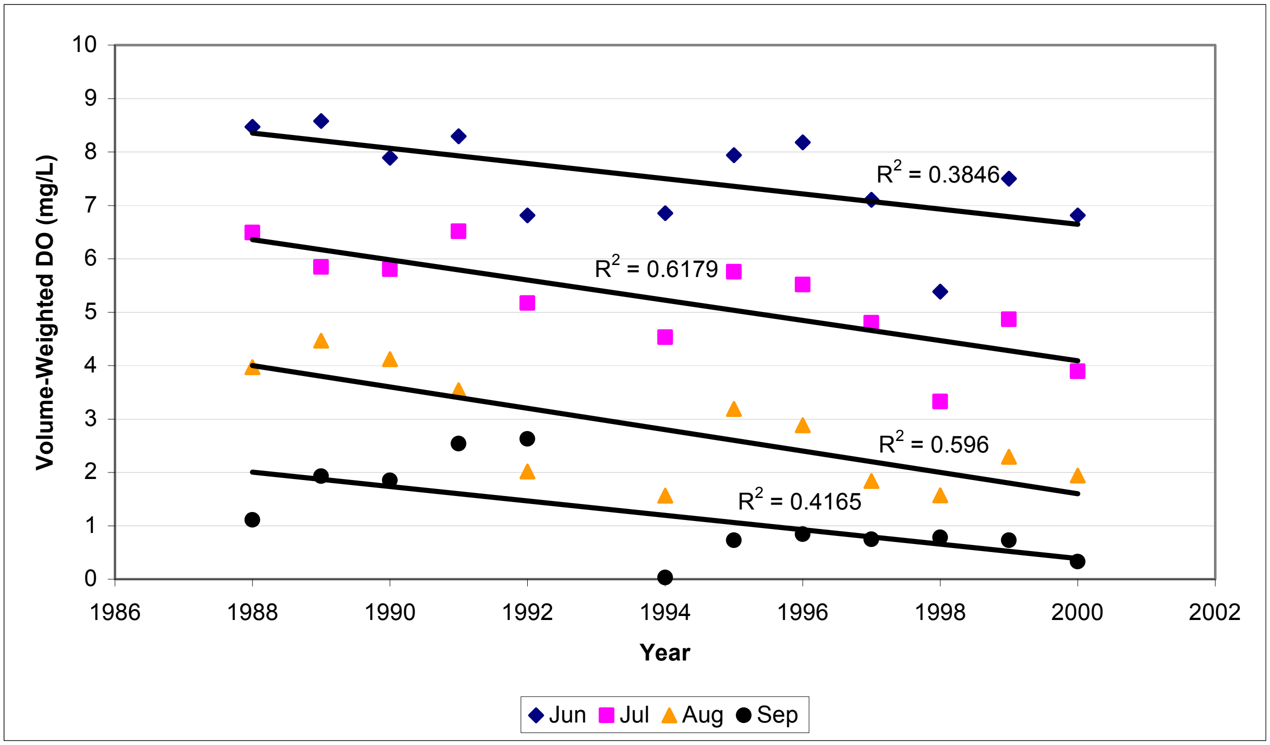


Figure 8. Correlation of Volume-Weighted Average Hypolimnetic Dissolved Oxygen Concentrations by Year at Site 1.

During late summer, total phosphorus concentrations were often higher than 20 µg/L at Sites 1 and 2, but the concentrations were relatively low at other sites. In addition, it was also found that increased phosphorus concentrations could occur during lake overturn. Over the years, Site 1 continued to develop the earliest and most prolonged period of anoxia in the lake, and it is more productive than the rest of the lake as indicated by the nutrient, chlorophyll, and oxygen data, as well as the total plankton counts. The recent data show that Site 2 had higher hypolimnetic concentrations of hydrogen sulfide, ammonia, and iron. All of these suggest that the anoxic conditions at Site 2 were at least as severe as at Site 1. Since most of the tributaries in Basins 1 and 2 are residential creeks or storm drains, they may bring in a large amount of organic matter and associated nutrients to the lake through surface runoff or storm overflow.

Generally, phytoplankton blooms occur as follows: diatoms peak in early summer, followed by dinoflagellates in late August, and blue-green algae in mid-autumn, and then diatoms peak again after the lake overturns. However, this pattern doesn't occur consistently in Lake Whatcom (Matthews Personal Communication). One possible reason is that the "up-lake" algae movement by subsurface water currents may result in lower phytoplankton counts than expected in Basin 1, and higher counts in Basin 3. Biovolume and chlorophyll concentrations are similar throughout the lake until July, then increase in Basin 1 and may remain high until late winter. However, biovolume has not been accurately measured since 1987 and the patterns may have changed in the past few years.

Previous silica data showed that silica concentration decreased in the epilimnion of Basins 1 and 2, but it is not clear whether it is limiting phytoplankton growth. It may be limiting diatom growth in summer. However, silica has not been measured in the lake since 1987 (Matthews Personal Communication).

Based on the multi-year monitoring results of Matthews et al., the residential creeks had poor water quality compared to forested creeks in Lake Whatcom. Like most of the typical streams receiving urban runoff, the residential creeks in the Lake Whatcom basin have higher conductivity and concentrations of ammonia, phosphorus, total suspended solids, and much higher total and fecal coliform counts. These tributaries are considered to be the major pollutant contributors to the lake. Although Silver Beach Creek is the only tributary on the 1998 303(d) list for fecal coliform, elevated levels of fecal coliform have also been observed in some other creeks, such as Austin Creek and Park Place, as shown in Figure 9.

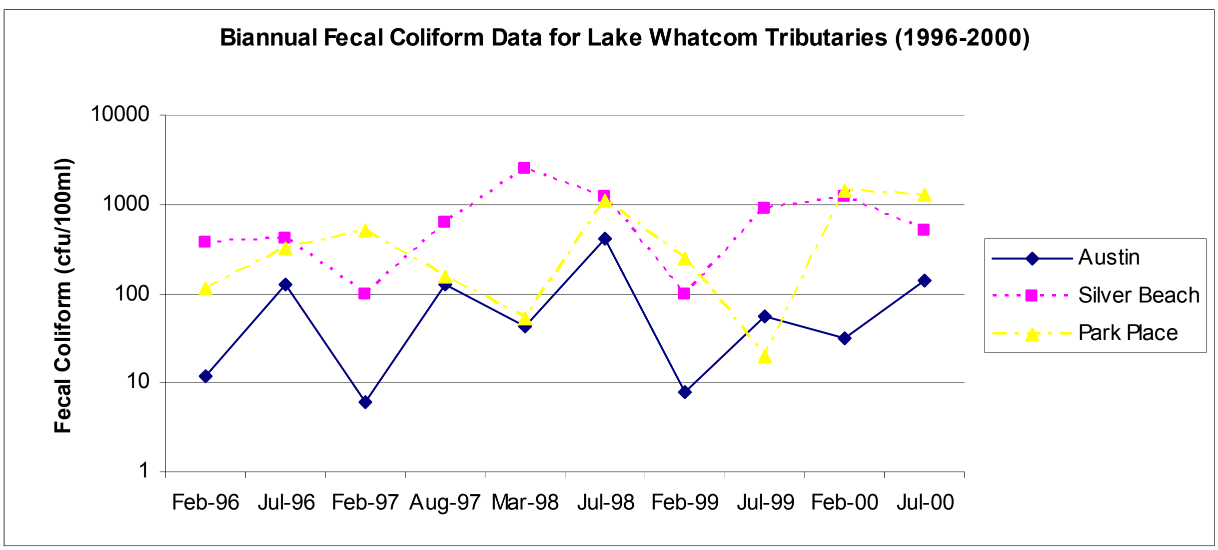


Figure 9. Biannual Fecal Coliform Data for Lake Whatcom Tributaries (1996-2000).

Although a large amount of water quality data are available for the lake, due to lack of stream flow data and groundwater data, it is not possible to correctly estimate the nutrient loading to the lake using historical data. Thus, it is also not possible to calibrate a water quality model until more tributary data are collected. This is one of the major gaps in the historical data. In addition to measuring the tributary flow and water quality, it is also very important to identify groundwater inflow and water quality.

Project Goals and Objectives

The major goal of this project is to quantify the impacts of pollutants that affect dissolved oxygen concentrations in Lake Whatcom, and make recommendations for limits of these pollutants with respect to the assimilative capacity of the lake. Another goal of this project is to quantify the concentrations of bacteria in some of the tributaries to Lake Whatcom and make recommendations for limits that will meet the water quality criteria. The specific objectives are as follows:

- Develop a two-dimensional hydrodynamic and water quality model (CE-QUAL-W2 model) of Lake Whatcom to determine the capacity of the lake to assimilate sources of oxygen-consuming substances (i.e., pollutants that directly or indirectly exert an oxygen demand).

- Gather existing data, and conduct water quantity and water quality sampling surveys that can be used to calibrate the CE-QUAL-W2 model.

- Use the CE-QUAL-W2 model to determine the potential to violate the dissolved oxygen criterion.

- Recommend potential wasteload allocations (WLAs) for point sources and load allocations (LAs) for nonpoint sources of oxygen-consuming substances (direct and indirect) that will meet dissolved oxygen criteria.

- Collect bacteria data and quantify the distribution of bacteria concentrations in the Silver Beach, Austin Creek, and Cable Street drainages.

- Determine bacteria load allocations for Silver Beach, Austin Creek, Park Place, and Cable Street drainages that will meet the water quality criteria.

Study Design

Approach

Currently several studies on Lake Whatcom and its watershed are being conducted by different entities with various goals and objectives. The WRIA1 Watershed Management Project contracted with Utah State University (USU) to conduct a watershed study and develop a water resource management model. COB contracted with WWU to continue the annual Lake Whatcom Monitoring Project with the objective of providing long-term baseline water quality data for the lake. Our project is focused on developing a hydrodynamic water quality model that can be used to set TMDL limits for the lake. Ecology will coordinate all sampling with those entities working on the lake and watershed to minimize replication of effort.

Four field sampling approaches will be used to achieve the objectives of this study.

- Synoptic sampling: comprehensive concurrent sampling of nine major tributaries and storm drains to the lake. These tributaries are considered to be significant contributors of pollutants to the lake. Two additional storm drains will be sampled for fecal coliforms and E. coli. All samples will be grab samples.

- Storm sampling: flow-proportioned composite samples will be collected at six tributaries during three storm events. The purpose of this survey is to understand the significance of pollutant loading from those tributaries during storms. The six tributaries selected are: Anderson, Austin, Euclid, Silver Beach, Olsen, and Smith Creeks. If a stable rating cannot be established for Silver Beach Creek, Mill Wheel will replace it. To coordinate with the modeling needs of the WRIA1 Watershed Management Project, discrete samples will be collected for two storms at each site. The analysis of the discreet samples will be averaged to estimate the average loading for use in the CE-QUAL-W2 model.

- Diagnostic limnological sampling: profile data and discrete samples collected at different depths.

- Groundwater sampling: groundwater sampling will be conducted under a separate QA Project Plan and will not be summarized here. Groundwater sampling will be conducted in support of this project and coincide with the lake and tributary sampling.

The historical data and data collected from these field surveys will then be used to calibrate a hydrodynamic and water quality model of the lake, which will be used to predict dissolved oxygen concentrations and other water quality constituents under different management scenarios. The model results will be used to determine the amount of pollutant loading reduction needed to meet the dissolved oxygen water quality criterion by allowing no more than a 0.2 mg/L deficit at any point in the water column.

Field Studies

Tributary Sampling

The field sampling survey will be conducted from July 2002 through October 2003 every three weeks. The COB began sampling the tributaries in January 2002, and Ecology will take over the sampling in July 2002.

Nine tributaries have been selected for the lake response portion of this study based on their relative ease of access and impact on the lake with consideration of their current land use and potential development (Figure 10). The selected tributaries are: Anderson, Austin, Smith, Euclid, Silver Beach, Olsen, Brannian, Mill Wheel, and Carpenter Creeks. These tributaries represent different drainage characteristics of the watershed. Table 3 summarized the location, gauging, and sampling strategy for each site. For detailed site description, see Table 1 of Appendix A.

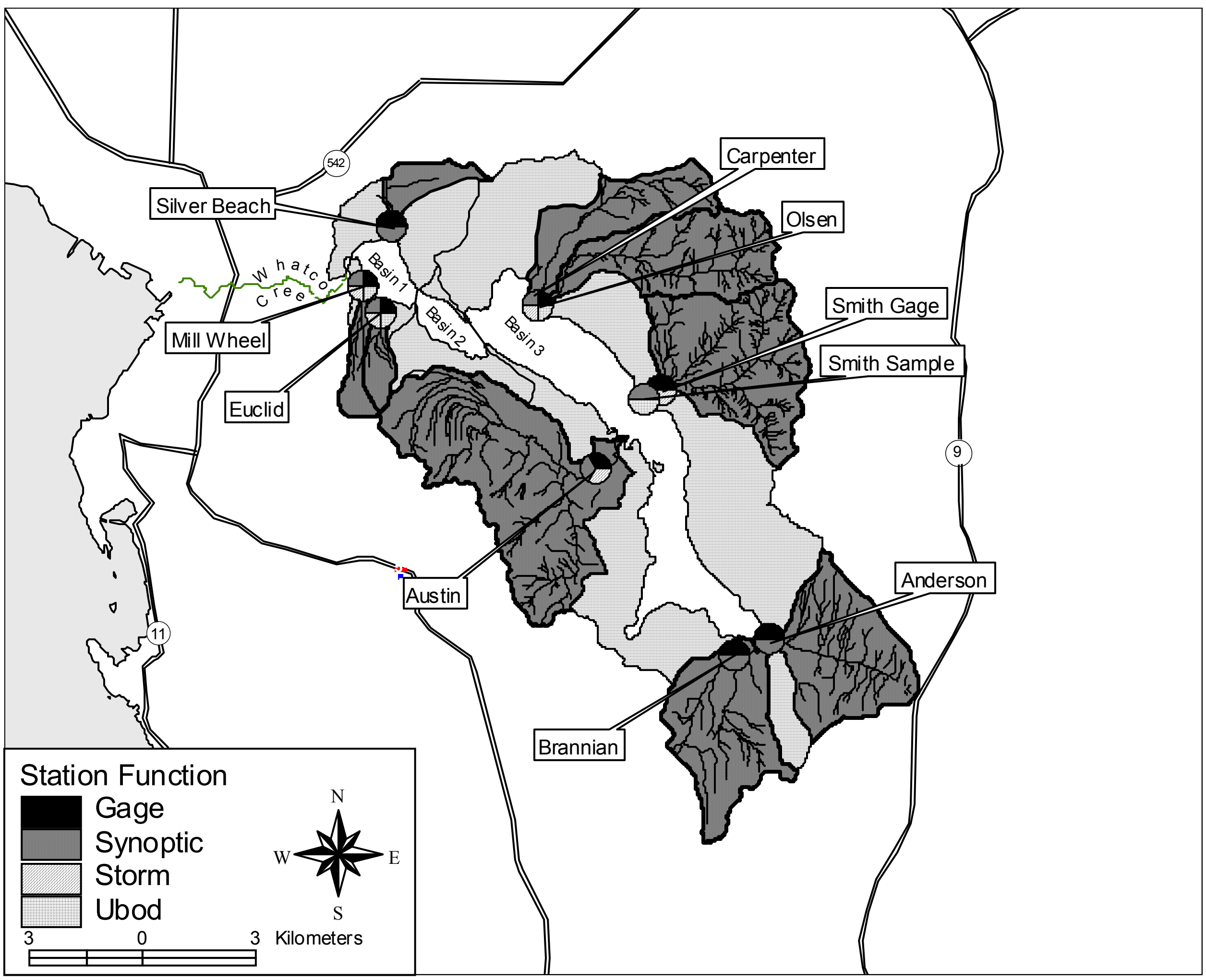


Figure 10. Lake Whatcom Tributary Gauging and Sampling Stations.

Table 3. Tributary Sampling Sites Information.

Station	Northing	Easting	Gage Operator	Gage	Synoptic	Storm	UBOD Silicon
Brannian	1221743	1569985	USGS	X	X		
Anderson	1223179	1573026	WWU	X	X		
Austin	1237962	1557959	WWU	X	X	X	
Euclid	1251471	1539299	USGS	X	X	X	X
Smith Gage	1244739	1563605	WWU	X		X	
Smith Sample	124394	1562142			X		X
Olsen	1252072	1552897	USGS	X	X	X	X
Carpenter	1252852	1552498	USGS	X	X	X	
Mill Wheel	1253829	1537738	USGS	X	X	*	X
Silver Beach	1258983	1540236	USGS	X	X	X*	

* Silver Beach Creek is the preferred storm sampling site. If a stable rating in Silver Beach Creek cannot be developed, Mill Wheel Creek will be used as a substitute.

The Northings and Eastings are coordinates in feet for the Washington State Plane South Zone, using the North American Datum of 1927. Smith Creek has two locations. Smith Gage is the site that has been gauged for many years where North Shore Drive crosses Smith Creek in a deep gorge. For the tributary sampling, a more accessible site further downstream, identified as Smith Sample, has been selected.

Samples will be collected from the nine tributaries every three weeks at or near the confluence with the lake at the location shown in Table 3. Sampling frequency and parameters measured are listed in Table 4. Temperature data will be collected every 30 minutes from the nine tributaries by using in situ temperature thermisters, which are placed near each of the flow gauges. COB staff will download the data from the thermisters every two weeks. Stream flow data will also be collected on these tributaries but at 15-minute intervals. At the time of this proposal, seven tributaries--Anderson, Austin, Smith, Euclid, Silver Beach, Olsen, and Brannian Creeks--all have continuous flow loggers installed, which are capable of recording flow data at the specified intervals. Gauges are in the planning stage for Mill Wheel and Carpenter Creek, and will be installed sometime in the near future. Outflow of the lake outlet and the city water withdrawal is currently being measured by COB; no additional outflow will be measured for this study. pH, conductivity, and DO will be measured in situ, and all of the other parameters will be analyzed in the lab from the grab samples based on standard protocols specified for this study.

Table 4. Tributary Sampling Frequency and Proposed Analytes for July 2002 through October 2003.

Parameter	Frequency	Storm Sampling (3 events)	Storm Sampling Discrete (Samples per event)	Routine Sampling (grabs)	Non-Routine Sampling (grabs)
Field Measurements					
Temperature	in-situ continuous		High frequency	High Frequency	
Electrical Conductivity	Every 3 wks grab, 9 sites, in situ		High Frequency		
Dissolved Oxygen	Every 3 wks, 9 sites, in situ		High Frequency		
pH	Every 3 wks, 9 sites, in situ		High Frequency		
General Chemistry					
Total Dissolved Solids	3 sites every 3 wks and 6 sites storm (x3)	**X**	**6**	**X**	
Total/Dissolved Organic Carbon	9 sites every 3 wks and 6 sites storm (x3) *	**X**	**12**	**X**	
Soluble Reactive Phosphorus	9 sites every 3 wks and 6 sites storm (x3)	**X**	**12**	**X**	
Total Phosphorus	9 sites every 3 wks and 6 sites storm (x3)	**X**	**12**	**X**	
Nitrate-Nitrite Nitrogen	9 sites every 3 wks and 6 sites storm (x3)	**X**	**6**	**X**	
Ammonia Nitrogen	9 sites every 3 wks and 6 sites storm (x3)	**X**	**6**	**X**	
Total Persulfate Nitrogen	9 sites every 3 wks and 6 sites storm (x3)	**X**	**6**	**X**	
Total Suspended Solids	9 sites every 3 wks and 6 sites storm (x3)	**X**	**12**	**X**	
Volatile Suspended Solids	9 sites every 3 wks and 6 sites storm (x3)	**X**		**X**	
Chlorophyll *a*	9 sites, every 3 weeks		**2**	**X**	
Total/Dissolved Silicon	9 sites, 6 samples per site		**6**	**X**	6 per site
Alkalinity	9 sites every 3 wks and 6 sites storm (x3)	**X**	**6**	**X**	
Fecal Coliform/E.coli	11 sites every 3 wks	**X**	**6**	**X**	
BOD5*			**X**	**X**	
Ultimate BOD	3 sites, 3 samples per site				3 per 3 sites

* Dissolved organic carbon sampled every other survey.
* Sampling shaded is added for USU watershed project.
* COB will do some BOD5 samples.

Two additional stations will be sampled for E. coli and fecal coliforms only. One site is the Cable Street drain. The sample will be collected from the Manhole at Cable Street and Lake Whatcom Boulevard. The other site is at Park Place. The sample will be collected from the manhole downstream of the Park Place Pond where the pond flow and bypass flows combine. Flows at both stations will be estimated by depth of flow in the culvert.

Storm Events

Storm sampling will fill the needs of two different modeling efforts. The immediate need is to provide loading information relative to high flow conditions. The storm data will be used in conjunction with the tributary water quality data to develop multivariate regressions for predicting constituent loads for calibration of the CE-QUAL-W2 (Lake Response Model). For this purpose, composite samples will suffice. However, since USU is developing a spatially distributed watershed loading model (Watershed Model), the calibration of this model will require discrete samples over the course of a storm. In order to meet the requirements of the two models, composite sampling during one storm and discrete sampling during two storms will be conducted in this study.

Storm samples will be collected from six sites. The location and a brief description of each site can be found in Table 2 and Table 3 of Appendix A. In Table 4, the first storm sample column has an “X”, which indicates that the parameters will be measured in the composite samples for the Lake Response Model, and the second column has a number. The number represents the desired number of discrete samples to be collected during two storm events for calibration of the Watershed Model. The results of the discrete samples will be averaged for the Lake Response Model to represent the storm concentration. The third storm sampling event will only be a composite. The analysis shaded in Table 4 represents data that is being collected solely in support of the watershed model.

The goal of the storm sampling will be to characterize water quality for both the ascending and descending limb of the hydrograph. There were two gauging stations with fairly complete records in calendar year 2000: Austin and Smith Creeks. An analysis of the water quality data for these creeks paired with rainfall data from the Post Point Waste Water Treatment Plant (WWTP) shows that a storm of 0.5 inches will generate a significant runoff event, which has been defined as a runoff event with a peak value greater than the 90^{th} percentile of the 2000 record. Sampling in the wet season of 2002 indicated that 0.5 inches of rainfall increases sediment loads. To capture summer/early fall storms where the likelihood of measuring first flush will be the greatest, a similar prediction of significant flow will be developed specifically for the season.

All storm samples will be collected on a flow-paced basis. The volume of stream flow that must pass between samples for discrete samples and between sips of a composite sample will be based on a prediction of the total volume that will pass between the trigger value (tentatively at 90^{th} percentile of CY 2000 record) and the peak of the hydrograph. The prediction will be made based on regression analysis using antecedent and predicted rainfall for the Post Point WWTP.

For discrete samples, the predicted total volume in the ascending limb will be used to pace sampling to collect the predicted 6 samples on the ascending limb. In order to have sufficient volume for all of the required analyses, each discrete sample will consist of two one-liter bottles. The samplers will be checked shortly after the peak of the hydrograph is expected. Additional bottles will be placed in the sampler to ensure that some of the descending limb of the hydrograph is also sampled. The actual number of samples collected will be determined by the shape of the hydrograph but will not exceed the target number listed in Table 4.

One of the discretely sampled storms will be a first flush storm, and the other will be a storm with lower intensity but longer duration. At the beginning and the middle of the two discretely sampled storms, surface water samples will also be collected from the lake, near the middle of the plume of the creek flow, and the sampling sites will be approximately 100 feet off the mouths of each tributary sampled. The approximate locations are shown in Figure 11 The storm samples collected from the lake will be analyzed for chlorophyll *a*, total and dissolved silicon and fecal coliforms.

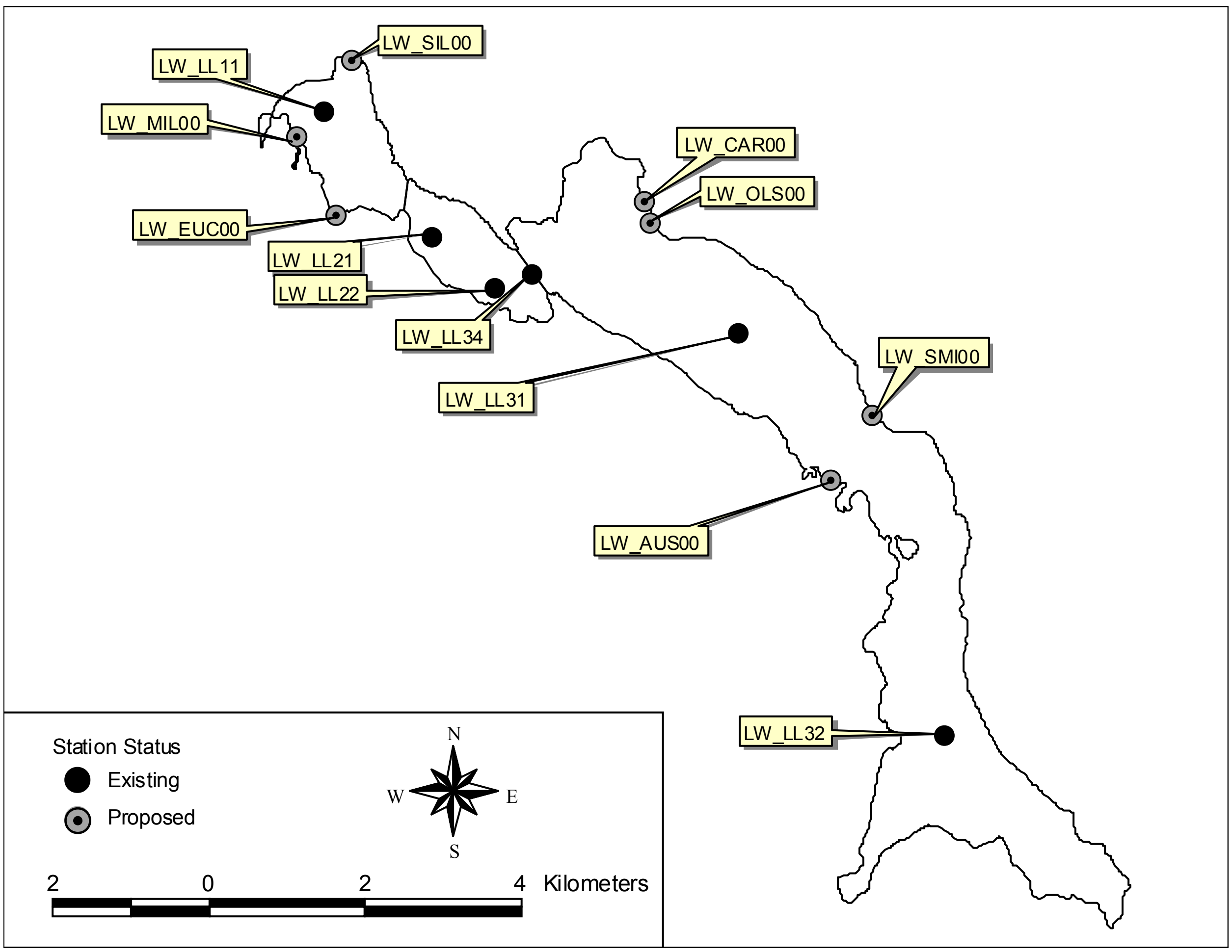


Figure 11. Lake Whatcom Lake Sampling Stations.

The third storm will be a composite sample. For each of the samples, the volume of water that will pass on the ascending limb of the hydrograph will be estimated. Each time 1/10 of that volume passes, a sub-sample will be collected. Gauges will be checked shortly after the peak of the hydrograph is predicted, and the samplers will be programmed to end sampling after an equal number of samples have been collected on the ascending and descending limb of the hydrograph, unless the sample is less than 4 liters. In this case, sampling will continue until there is sufficient volume.

Lake Sampling

Lake sampling and analysis will be conducted by WWU as part of their annual Lake Whatcom Monitoring Project (see Figure 11 and Appendix B), and additional variables will be added by Ecology for lake response model calibration (see Table 5). Water samples will be collected at five sites in the lake each month. Sites 1 and 2 (LW_LL11 and LW_LL21) are located in the deepest points of Basins 1 and 2, respectively. The intake site (LW_LL22) is located adjacent to the underwater intake point where COB withdraws raw water from Basin 2. Site 3 (LW_LL31) is located at the deepest point in the northern sub-basin of Basin 3, and Site 4 (LW_LL32) is located at the deepest point in the southern sub-basin of Basin 3. For detailed site description, see Table 2 and Table 3 of Appendix A.

Table 5. Supplementary Lake Whatcom Sampling Strategy and Parameters Measured.

Parameter	Sampling Schedule															Location
	2002						2003									
	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	
TDS	*	*	*									*	*	*	*	Sites 1, 2, 3, 4 – 0.3, 5, 15m
TOC/DOC*	*	*	*	*	*	*		*		*	*	*	*	*	*	Sites 1, 2 – 0.3, 10, 20 m; Site 3 – 0.3, 10, 20, 80 m; Site 4 – 0.3, 5, 10, 20, 80, 90 m;
Total/Dissolved Silicon	*	*	*									*	*	*	*	Sites 1, 2, 3 – 0.3, 5
CBODU		*												*	*	Sites 1, 2, 3 – hypolimnion
Phytoplankton	*	*	*								*	*	*	*	*	Sites 1, 2, 3 – 0.3, 5, 10m
Light Transmission	*	*	*	*							*	*	*	*	*	Sites 1, 2, 3, 4

* Only half of the samples will be analyzed for DOC.

Data Quality Objectives and Analytical Procedures

Sampling, laboratory analysis, and data evaluation steps have several sources of error that should be addressed by data quality objectives. Accuracy in laboratory measurements (measurement quality objectives) can be more easily controlled than field sampling variability. Analytical bias needs to be low and precision as high as possible in the laboratory. Sampling variability can be somewhat controlled by strictly following standard procedures and collecting quality control samples, but natural spatial and temporal variability can contribute greatly to the overall error in the parameter value. Resources limit the number of samples that can be taken at one site spatially or over various intervals of time. Finally, laboratory and field errors are further expanded by estimate errors in seasonal loading calculations and modeling estimates.

The data quality objectives of both field measurements and laboratory analyses are summarized in Table 6.

Table 6. Summary of Targeted Accuracy for Field Measurements and Laboratory Analyses, and Precision, Bias, and Reporting Limits for Laboratory Analyses.

Analysis	**Accuracy** % deviation from true value	**Precision** Relative Standard Deviation	**Bias** % deviation from true value	**Required Reporting Limits** Concentration units
Field Measurements				
pH*	0.15 s.u.*			
Water Temperature*	0.2°C*			
[1]Dissolved Oxygen	0.2 mg/L*			
Electrical Conductivity	10 µmho/cm*			
Secchi Disc Depth		0.5 m		
Light Attenuation		0.0014 $\mu W/cm^2$		
Laboratory Analyses				
Biochemical Oxygen Demand	N/A	25	N/A	2 mg/L
Ultimate Biochemical Oxygen Demand	N/A	25	N/A	2 mg/L
Chlorophyll a	N/A	20	N/A	0.05 µg/L
Total Organic Carbon	30	10	10	1 mg/L
Dissolved Organic Carbon	30	10	10	1 mg/L
Total Suspended Solids	30	10	10	1 mg/L
Total Dissolved Solids	30	10	10	1 mg/L
Total Nonvolatile Suspended Solids	N/A	10	N/A	1 mg/L
Alkalinity	N/A	10	N/A	5 mg/L
Total Persulfate Nitrogen	30	10	10	25 µg/L
Ammonia Nitrogen	25	10	5	10 µg/L
Nitrate & Nitrite Nitrogen	25	10	5	10 µg/L
Orthophosphate P	25	10	5	5 µg/L
Total Phosphorus	25	10	5	3 µg/L
Total Silica	25	10	5	0.05 mg/L
Dissolved Silica	25	10	5	0.05 mg/L
Fecal Coliform (MF)	N/A	25 [2]	N/A	1 cfu/100 mL
E. Coli	N/A	25	N/A	1 cfu/100 mL
Phytoplankton	N/A	N/A	N/A	N/A

[1] Hydrolab data will be calibrated using Wrinkler titration method.
[2] Log transformed data.
* as units of measurement, not percentages.

Our targets are the percentage values except for concentrations near the reporting limit where the allowed errors are either equal to the percentage or required limit, whichever is greater.

Sampling and Quality Control Procedures

Collecting replicate samples will assess total variation for field sampling and laboratory analysis and thereby provide an estimate of total precision. At least 10% of the total number of laboratory samples per parameter and field measurements will be replicate samples. In addition, field blanks will be collected to determine the presence of positive bias in the analytical method.

Field sampling and measurement protocols will follow those specified in WAS (1993) for temperature (alcohol thermometer), pH (Orion Model 250A meter and Triode™ pH electrode), electrical conductivity (Beckman Model RB-5 and YSI 33), dissolved oxygen (Winkler titration), and *in situ* temperature, dissolved oxygen, pH, and electrical conductivity (Hydrolab® multi-parameter meters). All meters will be calibrated and post-calibrated per manufacturer's instructions. For dissolved oxygen measurement, hydrolab result will be calibrated and compared with Winkler titration method.

Analytical methods, sample containers, volumes, preservation, and holding times for laboratory analysis are listed in Table 7. All water samples for laboratory analysis will be collected in pre-cleaned containers supplied by MEL, except dissolved organic carbon and orthophosphate (soluble reactive phosphorus), which will be collected in a syringe and filtered into a pre-cleaned container. The syringe will be rinsed with ambient water at each sampling site three times before filtering. All samples for laboratory analysis will be preserved as specified by MEL (2000) and delivered to MEL within 24 hours of collection. Laboratory analyses listed in Table 7 will be performed in accordance with MEL (2000).

Table 7. Summary of Laboratory Measurements and Methods.

Parameter	Bottle	Preservative	Holding Time	EPA Method	Manchester Lab Reporting Limit
Alkalinity	500 mL polypropylene (poly)	Cool to 4ºC	14 days	310.2	5 mg/L
Biochemical Oxygen Demand (BOD)	1 gallon cubitainer	Cool to 4ºC	48 hours	405.1	2 mg/L
Ultimate Biochemical Oxygen Demand (BOD)	1 gallon cubitainer	Cool to 4ºC	48 hours	5210C	2 mg/L
Chlorophyll *a*	1000 mL amber	Cool to 4ºC	24 to filter 28 hours after filter	SM 10200H(3)[1]	0.05 ug/L
TOC	60 mL poly	HCl to pH<2, Cool to 4ºC	28 days	415.1	1.0 mg/L
DOC	60 mL poly	HCl to pH<2, Cool to 4ºC	28 days	415.1	1.0 mg/L
Ammonia	125 mL clear poly	H_2SO_4 to pH < 2, Cool to 4ºC	28 days	350.1	0.01 mg/L
Nitrate/Nitrite	125 mL clear poly	H_2SO_4 to pH < 2, Cool to 4ºC	28 days	353.2	0.01 mg/L
Nitrogen – Total Persulfate	125 mL clear poly	H_2SO_4 to pH < 2, Cool to 4ºC	28 days	SM4500[1]	0.025 mg/L
Orthophosphate	125 mL amber poly	Cool to 4ºC	48 hours	356.3	0.005 mg/L
Phosphorus, Total	125 mL clear poly	H_2SO_4 to pH < 2, Cool to 4ºC	28 days	365.3	0.01 mg/L
Phosphorus, Total Low Level	New 125 mL poly	H_2SO_4 to pH < 2, Cool to 4ºC	28 days	365.1	0.003 mg/L
Phytoplankton	500 mL amber	Lugol's solution	n/a	SM18 10200F; Sweet (1987)	n/a
Total Suspended Solids	1000 mL poly	Cool to 4ºC	7 days	160.3	1 mg/L
Total Nonvolatile Suspended Solids	1000 mL poly	Cool to 4ºC	7 days	160.4	1 mg/L
Total Dissolved Solids	500 mL poly	Filter, then HNO3 to pH<2	7 days	160.1	1 mg/L
Total Silica	1L HPDE	HNO3 to pH<2	6 months	600/4-79-020, 4.1.1.	0.05 mg/L
Dissolved Silica	1L HPDE	Cool to 4ºC	6 months	600/4-79-020, 4.1.1.	0.05 mg/L
Fecal Coliform	250 mL glass/poly autoclaved	Cool to 4ºC	30 hours	SM MF 9222D	1 cfu/100 mL
E Coli	250 mL glass/poly autoclaved	Cool to 4ºC	30 hours	1103	1 cfu/100 mL

[1] SM indicates Standard Methods rather than EPA method.

Data Analysis and Water Quality Modeling

Data Analysis

Data analysis will include estimation of univariate statistical parameters (arithmetic mean, median, standard deviation, and range of data by station and sampling survey). Field duplicate samples will be used to assess total variability and determine if the project data meet the data quality objectives for precision. Laboratory split and laboratory quality control samples will be used to assess analytical variability and determine if the project data meet the data quality objectives for accuracy. The estimates of total and analytical variability will be compared to describe the relative contributions of variability from sampling and analytical methods and natural conditions.

Using the tributary sample data, a log linear regression model will be used to estimate the daily fluvial loads for each tributary to Lake Whatcom. The log linear model requires estimation of a constant, a linear and quadratic fit to the logarithm of flow, and sinusoidal (Fourier) functions to account for the effect of annual seasonality:

$$\log(C) = b_o + b_1 {*}\log(Q) + b_2 {*}\log(Q)^2 + b_3 {*}\sin(2\pi T) + b_4 {*}\cos(2\pi T) + b_5 {*}\sin(4\pi T) + b_6 {*}\cos(4\pi T) + \varepsilon$$

Log (C) is the logarithm of each parameter concentration, log Q is the logarithm of flow, and T is time measured in years. The error term (ε) is assumed to be independent and normally distributed with zero mean. The b terms are the parameters of the model that must be estimated from multiple regressions.

Relationships between sub-basin area, land-use, and variable concentrations and loading will be used to extrapolate values to all drainages (i.e., including those drainages not monitored).

The statistical model will be used to estimate daily, seasonal, and annual loading of all parameters. The Statistical Theory of Rollback (STR) from Ott (1995) will be applied to the estimated distributions of *fecal coliform* and *E.coli* to establish distribution statistics that meet the water quality criteria (i.e., geometric mean and 90^{th} percentile).

Water Quality Modeling

A dynamic 2-dimensional water quality model CE-QUAL-W2 will be developed for Lake Whatcom. Figure 11 shows the CE-QUAL-W2 grid which consists of direct-coupled hydrodynamic and water quality transport models. CE-QUAL-W2 was designed to simulate stratified reservoirs with wind driven currents and selective withdrawals from dams, pipes, spillways, and weirs. In addition to modeling temperature, CE-QUAL-W2 simulates more than 20 other water quality variables. The primary physical processes CE-QUAL-W2 can simulate are surface heat transfer, short-wave and long-wave radiation and penetration, convective mixing, wind and flow induced mixing, entrainment of ambient water by pumped-storage inflows, inflow density stratification as affected by temperature, and dissolved and suspended solids. Major chemical and biological processes that CE-QUAL-W2 can simulate are the effects of atmospheric dissolved oxygen exchange, photosynthesis, respiration, organic matter decomposition, nitrification, and chemical oxidation of reduced substances; and uptake, excretion, and regeneration of phosphorus and nitrogen and nitrification-denitrification under aerobic and anaerobic conditions; carbon cycling and alkalinity-pH-CO_2 interactions; trophic relationships for total phytoplankton; accumulation and decomposition of detritus and organic sediment; and bacteria mortality (Cole and Wells, 2001).

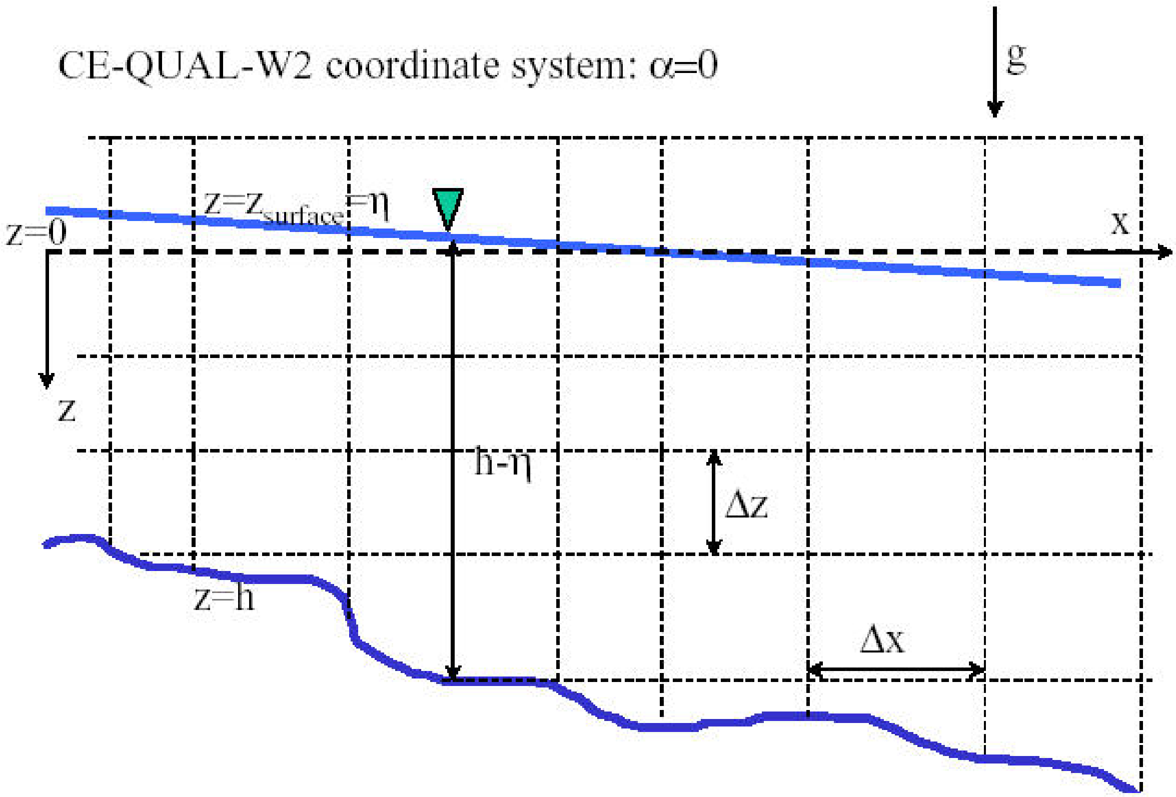


Figure 12. Coordinate System for CE-QUAL-W2 Version 3.1.

Project Schedule and Laboratory Budget

The schedule for the proposed study is as follows:

Submit Draft QAPP for Internal Review	April 30, 2002
Submit Draft QAPP for Client Review	May 15, 2002
Submit Draft QAPP for Public Review	May 30, 2002
Finalize QAPP	June 30, 2002
Sampling Surveys Begin	July 2002
Sampling Surveys End	September 2003
Draft Report	April 30, 2004
Final Report	July 31, 2004

The laboratory budget is presented in Table 8. The cost of collecting and analyzing "extra" samples will be paid for by the Lake Whatcom Management Committee. The monthly budget for the TMDL study is summarized in Table 9.

Table 8. Lab Cost for the Proposed TMDL Study Including Extra Cost for the Watershed Model.

Lab Measurement Parameter	Sampling Quantity				Unit Cost	Cost (includes replicates)			
	TMDL	Discrete Storm Sampling	Additional Routine Sampling (Grabs)	Total (include 10% replicates)		TMDL	Discrete Storm Sampling	Additiional Routine Sampling (Grabs)	Sub Total
Tributaries									
Alkalinity	198	60		284	$14	$3,051	$924		$3,976
Total Dissolved Solids	78	60	120	284	$10	$859	$660	$1,321	$2,840
Total Suspended Solids + Total Non-Volatile Suspended Solids (TNVSS)	198	132		363	$21	$4,574	$3,049		$7,623
Total organic carbon	198	132		363	$29	$6,316	$4,211		$10,527
Dissolved organic carbon	99	138		261	$29	$3,162	$4,407		$7,569
Nutrient 5 (include TPN)	198	132		363	$53	$11,543	$7,696		$19,239
Low Level TP	99	66		182	$20	$2,184	$1,456		$3,640
Chlorophyll a	180	24		225	$46	$9,132	$1,218		$10,350
Total Silicon	54	72	126	278	$24	$1,430	$1,906	$3,336	$6,672
Dissolved Silicon	54	72	126	278	$24	$1,430	$1,906	$3,336	$6,672
Fecal Coliform	238	60		328	$20	$5,239	$1,321		$6,560
E.coli	238	60		328	$35	$9,169	$2,311	$0	$11,480
BOD5*									
Ultimate CBOD	9			10	$521	$5,210			$5,210
Sub Total (Tributaries)						**$63,299**	**$31,066**	**$7,993**	**$102,358**
Lakes									
Total Dissolved Solids	84			93	$10	$930			$930
Total organic carbon	208			229	$29	$6,641			$6,641
Dissolved organic carbon	104			115	$29	$3,335			$3,335
Total Silicon	42	24		73	$24	$1,115	$637		$1,752
Dissolved Silicon	42	24		73	$24	$1,115	$637		$1,752
Phytoplankton	72			80	$64	$5,120			$5,120
Ultimate CBOD	9			11	$521	$5,731			$5,731
Chlororophyll a		24		27	$53		$1,431		$1,431
Fecal Coliform		24		27	$20		$540		$540
Sub Total (Lakes)						**$23,987**	**$3,245**		**$27,232**
Total						**$87,285**	**$34,311**	**$7,993**	**$129,590**

**COB Wastewater Treatment Plant lab will do some BOD5 samples

** The lab prices represent 50% of the total lab cost; the other 50% is paid through base funding provided by the Watershed Ecology Section.

Budget Summary:

TMDL Lake Response	**$87,285**
Watershed Model	**$42,304**
Total	**$129,589**

Table 9. Monthly Budget for TMDL Study.

	FY03												FY04			Total
Month	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	
Monthly Budget	$5,731	$7,642	$5,731	$6,377	$4,640	$4,640	$3,873	$4,640	$5,609	$4,640	$7,017	$5,731	$5,731	$7,642	$7,642	$87,285

Project Responsibilities

The following individuals and organizations will be involved in the project:

Bob Cusimano (Ecology): Project Manager. Responsible for overseeing all elements of the project and overall project design (360-407-6688).

Jing Liu (Ecology): Principal Investigator. Responsible for preparation of QA Project Plan, collecting and analyzing data, developing graphs and figures, and writing and editing draft and final reports (360-407-7451).

Will Kendra (Ecology): Section Supervisor of the Watershed Ecology Section of the Environmental Assessment Program. Responsible for approving the project QA Project Plan, project budget, and project reports (360-407-6698).

Karol Erickson (Ecology): Unit Supervisor of the Water Quality Studies Unit of the Environmental Assessment Program. Responsible for internal review of the project QA Project Plan and project reports (360-407-6694).

Richard Grout (Ecology): Client for the Water Quality Program of Ecology, Bellingham Field Office. Responsible for approving the QA Project Plan and final report and interacting with the stakeholders and other interested public (360-738-6255).

Steve Hood (Ecology): Assistant Project Manager. Responsible for developing the summary and detailed implementation plans for the TMDL and coordinating responsibilities for distributing data between Ecology, COB, USU, and WWU (360-738-6254).

Dean Momohara and Pam Covey (Ecology): Manchester Environmental Laboratory (MEL) staff responsible for analysis and reporting of chemical data (360-871-8860).

Cliff Kirchmer (Ecology): Responsible for review of the project QA Project Plan. Also will be available for technical assistance on QA issues during project implementation (360-407-6455).

Peg Wendling (City of Bellingham): Laboratory assistance with samples that need preservation or holding prior to shipping. Assistance with equipment needs associated with storm sampling. Coordinate lake samples associated with discrete storm samples (360-676-7689).

Joan Vandersypen (Western Washington University): Research Supervisor for Institute for Watershed Studies. Responsible for supervision of analysis of samples from in-lake monitoring (360-650-7384).

Michael Hilles (Western Washington University): Research Technologist for Institute for Watershed Studies. Responsible for coordination of in-lake monitoring for IWS (360-650-6587).

Sue Blake (Whatcom County): WRIA1 Watershed Management Project, Water Quality Technical Team. Lead responsible for coordinating input from local governments (360-676-6876).

David Stevens (or Beth Neilson) (USU): Lead researcher for WRIA1 responsible for developing loading models to be used to evaluate future conditions.

References

Delahunt, R. 1990. Lake Whatcom Watershed On-Site Sewage Disposal Survey. Final Report. Whatcom County Health Department Office of Environmental Health.

Hisch Consulting Services. 1998. Lake Whatcom Watershed-Cooperative Drinking Water Protection/Sampling. Narrative Description and Quality Assurance Plan. Prepared for the Washington State Department of Ecology.

Lighthart B., G. F. Kraft, and C. J. Charles. 1972. The Limnology of Lake Whatcom, Washington. Morphometry. Institute for Freshwater Studies. Technical Report No. 15.

Matthews, R. A., M. Hilles, G. Pelletier. 2002. Determining Trophic State in Lake Whatcom, Washington (USA), a Soft Water Lake Exhibiting Seasonal Nitrogen Limitation. Hydrobiologia 468: 107-121.

Matthews, R. A., J. Vandersypen, M. Hilles, R. J. Mitchell, and G. B. Matthews. 2002. Lake Whatcom Monitoring Project 2000-2001 Final Report. Final Report Prepared for the City of Bellingham Public Works Department. March, 2002. Bellingham, Washington.

Matthews, R. A., M. Hilles, J. Vandersypen, R. J. Mitchell, and G. B. Matthews. 2001. Lake Whatcom Monitoring Project 1999-2000 Final Report. Final Report Prepared for the City of Bellingham Public Works Department. March, 2001. Bellingham, Washington.

Matthews, R. A., M. Hilles, and G. B. Matthews. 2000. Lake Whatcom Monitoring Project 1998-1999 Final Report. Final Report Prepared for the City of Bellingham Public Works Department. April, 2000. Bellingham, Washington.

Matthews, R. A., M. Hilles, and G. B. Matthews. 1999. Lake Whatcom Monitoring Project 1997-1998 Final Report. Final Report Prepared for the City of Bellingham Public Works Department. April, 1999. Bellingham, Washington.

Matthews, R. A., M. Hilles, and G. B. Matthews. 1998 Lake Whatcom Monitoring Project 1996-1997 Final Report. Final Report Prepared for the City of Bellingham Public Works Department. February, 1999. Bellingham, Washington.

Matthews, R. A., M. Hilles, and G. B. Matthews. 1997. Lake Whatcom Monitoring Project 1995-1996 Final Report. Final Report Prepared for the City of Bellingham Public Works Department. April, 1997. Bellingham, Washington.

Matthews, R. A. and G. B. Matthews. 1995. Lake Whatcom Monitoring Project 1993-1994 Final Report. Final Report Prepared for the City of Bellingham Public Works Department. 1995. Bellingham, Washington.

Matthews, R. A. and G. B. Matthews. 1994 Lake Whatcom Monitoring Project 1992-1993. Final Report. Final Report Prepared for the City of Bellingham Public Works Department. 1994. Bellingham, Washington.

Ott, W. 1995. Environmental Statistics and Data Analysis. Lewis Publishers, New York, New York.

Pelletier, G. 1988. Dissolved Oxygen in Lake Whatcom: Trend in the Depletion of Hypolimnetic Oxygen in Basin 1 1983-1997. Washington State Department of Ecology. Ecology Report # 98-313.

Serdar, D. 1999. Lake Whatcom Watershed Cooperative Drinking Water Protection Project. Ecology Publication Number 99-337.

Serdar, D. 2001. Mercury Concentrations in Edible Muscle of Lake Whatcom Fish. Ecology Publication Number 01-03-012.

URS Corporation. 1985. Draft Lake Whatcom Water Quality Protection Study. Whatcom County, Washington: Volume 1, Technical Report and Volume 2, Management Plan.

U.S. Department of the Interior, Bureau of Reclamation. 2001. Lake Whatcom 1999-2000 Area and Capacity Survey.

WAS. 1993. Field Sampling and Measurement Protocols for the Watershed Assessments Section. Ecology Manual. Washington State Department of Ecology, Environmental Assessment Program. Olympia, Washington.

Walker, S. J., R. A. Matthews, and G. B. Matthews. 1992. Lake Whatcom Watershed Storm Runoff Monitoring Project. Final Report. Institute for Freshwater Studies. Prepared for the City of Bellingham Department of Public Works and the Washington State Department of Ecology.

Walker, S. J. 1995. Hydrologic Model for the Lake Whatcom Watershed Development. Implementation and Assessment. Western Washington University. Unpublished M.S.Thesis.

Wells, S. 2001. 2001, Hydrodynamic Modeling and Water Quality Modeling with Application to CEQUALW2. CEQUALW2 Workshop Notes 2001. Department of Civil Engineering. Portland State University. Portland, Oregon.

Western Washington State University. 1970. Factors Affecting the Movement of Water and Organisms within a Regulated Multipurpose Lake. Report to State of Washington Water Research Center.

Appendices

Appendix A

Appendix Table 1. Description of Tributary Sampling Sites.

STATION	DESCRIPTION
Anderson	The site is located at the bridge where South Bay Drive crosses the creek. The Anderson Creek gage is mounted in the existing stilling well on the east side of Anderson Creek, approximately 0.5 km from the mouth of the creek.
Austin	The site is approximately 1800 ft upstream from where the creek flows into Lake Whatcom. The Austin Creek gage is mounted on the north west support pillar under the bridge over Austin Creek (Lake Whatcom Blvd.), approximately 1 km from the mouth.
Brannian	Downstream of South Bay Drive, approximately 600 m from mouth
Cable Street	Catch basin near intersection of Cable Street and Lake Whatcom Boulevard
Carpenter	The site description is due soon.
Carpenter-road	Reserve
Euclid	East of Euclid Ave. 120 m from mouth. Upstream of public trail.
Mill Wheel	The site _will_ be at the upstream side of the culvert the passes under Flynn street
Olsen	The site is located at the bridge where North Shore Road crosses the creek. The gage is at the left bank upstream side of the bridge
Park Place	Catch Basin downstream of Park Place Pond
Silver Beach	Adjacent to Hayward Ct. Approx 130 m from mouth.
Smith Gage	The Smith Creek gage is mounted on the south wall of a sandstone bluff directly underneath the bridge over Smith Creek (North Shore Road) approximately 1 km upstream from the mouth of the creek.
Smith Sample	Samples are collected approximately 100 yards upstream from Lake Whatcom.

Appendix Table 2. Location of Lake and Storm Sampling Sites.

STATION	EIM_NAME	PROJ_NAME	DESCRIPTION	NORTHING	EASTING	LATITUDE	LONGITUDE
Intake	LW_LL21	Intake	Basin 2 intake	1251099	1543452	48.74816667	122.39117290
Site 1	LW_LL11	Site 1	Basin 1 deep - WWU Site 1	1256382	1538911	48.76233333	122.41050621
Site 2	LW_LL22	Site 2	Basin 2 deep - WWU site 2	1248968	1546058	48.74250000	122.38017290
Site 3	LW_LL31	Site 3	Basin 3N - WWU site 3	1247022	1556318	48.73783333	122.33750620
Site 4	LW_LL32	Site 4	Basin 3S - WWU site 4	1230147	1564950	48.69216667	122.30017289
Site S2	LW_LL34	Site S2	S'berry Sill - WWU Site S2	1249538	1547641	48.74416667	122.37367290
Austin Lake	LW_AUS00	Aust Lake	In Lake Nr. Austin Creek	1240827	1560143	48.72111367	122.32107873
Carpenter Lake	LW_CAR00	Carp Lake	In Lake Nr. Carpenter Creek	1252573	1552361	48.75278305	122.35442555
Euclid Lake	LW_EUC00	Eucl Lake	In Lake Nr. Euclid Creek	1251973	1539375	48.75029069	122.40814367
Mill Wheel Lake	LW_MIL00	Mill Lake	In Lake Nr. Mill Wheel Creek	1255263	1537743	48.75919073	122.41523170
Olsen Lake	LW_OLS00	Olse Lake	In Lake Nr. Olsen Creek	1251694	1552569	48.75038826	122.35347816
Silver Beach Lake	LW_SIL00	SB Lake	In Lake Nr. Silver Beach Cr.	1258512	1540053	48.76824076	122.40598923
Smith Lake	LW_SMI00	Smit Lake	In Lake Nr. Smith Creek	1243598	1561895	48.72881139	122.31408984

Appendix Table 3. Description of Lake and Storm Sampling Sites.

STATION	DESCRIPTION
Intake	The Intake Site is located offshore from the City of Bellingham's raw water gatehouse. The depth at the Intake site should be at least 13 m deep.
Site 1	Site 1 is located in basin 1 along a straight line from the Bloedel Donovan boat launch to a square, white house with a dark grey roof that is located about halfway up the hillside (171 E. North Shore Rd.) The sampling site is at a point perpendicular to the second group of condominiums in a cluster of four. The depth at Site 1 should be at least 20 m.
Site 2	Site 2 is located in basin 2 just west of the intersection of a line between a boat house with a rust-colored roof (73 Strawberry Point) and the point of Geneva sill, and a line between three aspen trees on Lake Whatcom Blvd. and a red house on the west side of Strawberry sill (2170 Delestra Rd.). The depth at Site 2 should be at least 20 m.
Site 3	Site 3 is located mid-basin just north of a line between the old railroad bridge and Lakewood. The depth at Site 3 should be at least 80 m deep.
Site 4	Site 4 is located at the intersection of a line between two points of land and a line parallel to the north edge of an inlet (see Figure A2). The depth at Site 4 should be at least 90 m deep.
Site S2	Site s2 is located approximately mid-channel between Delestra Park and Strawberry sill. The site is midway between a flat-roofed, brown-grey boathouse with red trim on the northeast point of Delestra Park and a white boathouse with two square windows just back from the north side of Strawberry point.
Austin Lake	Approximately 100 feet from Austin Creek mouth
Carpenter Lake	Approximately 100 feet from Carpenter Creek mouth
Euclid Lake	Approximately 100 feet from Euclid Creek mouth
Mill Wheel Lake	Approximately 100 feet from Mill Wheel Creek mouth
Olsen Lake	Approximately 100 feet from Olsen Creek mouth
Silver Beach Lak	Approximately 100 feet from Silver Beach Creek mouth
Smith Lake	Approximately 100 feet from Smith Creek mouth

Appendix B

Lake Whatcom 2001-2002 Monitoring Schedule by WWU

Parameter	2001 Oct	Nov	Dec	2002 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Location
DO - Hydrolab	•	•	•		•		•	•	•	•	•	•	Sites 1, 2, Intake - every 1 m;
pH - Hydrolab	•	•	•		•		•	•	•	•	•	•	Sites 3, 4 - every 1 m to 10 m
Temp - Hydrolab	•	•	•		•		•	•	•	•	•	•	then every 5 m;
Cond - Hydrolab	•	•	•		•		•	•	•	•	•	•	Gatehouse
Secchi disc	•	•	•		•		•	•	•	•	•	•	Sites 1, 2, 3, 4, Intake
Ammonia	•	•	•		•		•	•	•	•	•	•	Sites 1, 2 - 0.3, 5, 10, 15, 20 m;
Nitrite/Nitrate	•	•	•		•		•	•	•	•	•	•	Intake - 0.3, 5, 10 m;
Total Nitrogen	•	•	•		•		•	•	•	•	•	•	Site 3 - 0.3, 5, 10, 20, 40, 60,
Soluble Phosphate	•	•	•		•		•	•	•	•	•	•	80 m;
Total Phosphorus	•	•	•		•		•	•	•	•	•	•	Site 4 - 0.3, 5, 10, 20, 40, 60,
Alkalinity	•	•	•		•		•	•	•	•	•	•	80, 90 m;
Turbidity	•	•	•		•		•	•	•	•	•	•	Gatehouse
Total Arsenic											•		Sites 1, 2, 3, 4, Intake -
Total Cadmium											•		0.3 m and bottom only
Total Chromium											•		
Total Copper											•		
Total Iron											•		
Total Lead											•		
Total Mercury*	⊙	⊙	⊙		⊙		⊙	⊙			•		
Total Nickel											•		
Total Zinc											•		
Total O. Carbon					•						•		Sites 1, 2, 3, 4, Intake - 0.3 m and bottom only
Chlorophyll	•	•	•		•		•	•	•	•	•	•	Sites 1, 2, 3, 4 - 0.3, 5, 10, 15, 20 m; Intake - 0.3, 5, 10 m
Plankton	•	•	•		•		•	•	•	•	•	•	Sites 1, 2, 3, 4, Intake; 5 m
Bacteria	•	•	•		•		•	•	•	•	•	•	Sites 1, 2, 3, 4, Intake, Bloedel-Donovan; 0.3 m
H_2S - opt										•	•	•	Sites 1, 2 - 10, 15, 20 m

*Low level mercury sampling (⊙).