Major Lakes Continuous Temperature Study: Interim Progress Report

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King County

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EXECUTIVE SUMMARY

This report describes the initial results of a field sampling program to collect continuous (15 minute frequency) temperature profile data in three major lakes in King County (Sammamish, Washington and Union) using a variety of equipment and deployment methods. This sampling effort was initiated to provide temporal and spatial resolution of lake temperatures sufficient to evaluate the timing of spring stratification, development of diurnal thermoclines, the timing of lake turnover in the fall, data for coupling fish tracking thermistors with lake temperatures, and to support further hydrodynamic model testing and development. The monitoring equipment, approach, and goals are critically evaluated in this report and the following recommendations for changes to the current program are made:

- Use of Richard Brancker Research (RBR) thermistor chains should be discontinued.
- Initiate at least annual calibration checks of all temperature monitoring equipment, including profiling sondes used in the routine Major Lakes monitoring program.
- Additional thermistors should be added to Onset thermistor chains to provide temperature records at each location at 1-m intervals from the surface to at least the 30-m depth and perhaps every 2 to 5 meters thereafter.
- Reduce frequency of temperature recording from every 15 minutes to hourly.
- Check the depth of each Onset thermistor using a pressure transducer on at least an annual basis to verify the accuracy of the stated thermistor depths.
- Develop maintenance and performance logs for thermistors to help identify instruments requiring maintenance and instruments that are in working order.
- Ideally, telemetered monitoring buoys would replace the current system, which would eliminate bias due to bridge pontoons and should also minimize the field resources and post-processing effort currently expended downloading and managing the data from each thermistor or thermistor chain.
- Initiate more frequent profiles of phytoplankton biomass, possibly through the use of unattended profilers that include high quality *in situ* fluorometers to better understand the relationship between water column stability and phytoplankton bloom dynamics.
- Continuation of quantitative phytoplankton analysis, especially at the UW that would include the analysis of archived samples using similar techniques and level of training as in their past efforts.

A number of aquatic ecosystem responses to changing climate have been documented in Lake Washington and other lakes around the world. These responses could only have been detected and understood in the context of changing climate as the result of consistent long-term monitoring of physical, chemical, and biological components of the ecosystem. Further understanding of the effects of changing climate will come from continued comprehensive routine monitoring.

The initial continuous temperature monitoring effort described in this report, demonstrated the methods and utility of frequent temperature measurement in the three major lakes routinely monitored by King County. These data match less frequent routinely collected data in long-term warming trends but adds more precise information on dates and duration of seasonal stratification and periods of maximum (and minimum) temperatures. These data also inform fish and hydrodynamic studies that historic data cannot. Also, example uses of these data – Index of Thermal Stress (ITS), thermal stability calculations, and identification of internal seiches have been provided.

1.0. INTRODUCTION

Climate change as defined by the Intergovernmental Panel on Climate Change (IPCC) includes any change in climate over time due to natural variability or human activity (Karl and Trenberth 2003, IPCC 2001). The best studied and documented change in recent climate is an increasing trend in globally-averaged temperatures that the IPCC has concluded is at least partially due to human activities (IPCC 2001). Over the last century, globally-averaged surface temperatures have increased by $0.6 \pm 0.2\ ^{o}C$ (IPCC 2001). In the Puget Sound Region of the Pacific Northwest, the annual average 20th century warming was 1.5 ^{o}C – more than twice the warming observed for the globe, although removal of the effects of the El Niño/Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) resulted in a trend of 0.8 ^{o}C (Mote 2003). The greatest warming in the Puget Sound Region has been observed in the last 30 years with greatest warming during winter (JFM) and least during fall (OND) again influenced strongly by the ENSO and PDO (Mote 2003). Global climate model simulations predict the planet to warm by an additional 1.4 to 5.8 ^{o}C by 2100 relative to 1990 (IPCC 2001). The projected warming in the PNW ranges from 0.1 to 0.6 ^{o}C per decade through 2050 – a significantly higher rate than observed during the last century (Snover et al. 2005).

Increasing temperatures across the planet have been linked to shifts in the geographic range of species or in the timing of various behaviors (Parmesan and Yohe 2003, Walther et al. 2002, Cayan et al. 2001). Examples include earlier flowering of lilac and honeysuckle in the Western United States (Cayan et al. 2001), earlier breeding or singing of songbirds (Walther et al. 2002), and northward expansion of the range of the silver spotted skipper butterfly (Parmesan and Yohe 2003). Many of these shifts in geographic range and behavioral timing are related to advancement of spring warming in the Northern Hemisphere (Cayan et al. 2001). Vernal ecological shifts have also been identified in the aquatic biota of Lake Washington (e.g., Hampton et al. 2006a, Hampton 2005, Romare et al. 2005, Winder and Schindler 2004a, Winder and Schindler 2004b), one of the subjects of this report.

Consistent with observed global warming and predicted responses of moderate to large-sized lakes to increased air temperatures (Robertson and Ragotzkie 1990), lakes with consistent and detailed long-term temperature profile data have provided documentation of warming over the last century, including Lake Washington (Table 1). In addition to an overall lake warming trend, modeling and observations have indicated trends toward earlier onset of stratification, later timing of lake turnover, decreased frequency of deep-water mixing events, and an increase in the overall thermal stability of lakes (Coats et al. 2006, Winder and Schindler 2004a, Winder and Schindler 2004b, Livingstone 2003, Peeters et al. 2002, Schindler et al. 1990).

The ecological effects of lake warming are not as well documented, most likely due to the lack of consistently collected long term ecological data that might have accompanied the collection of long term physical measurements. Nonetheless, a few recent studies have linked ecological changes to lake warming. For example, an inverse correlation between spring ice-out date and primary productivity, and *Daphnia* and cyanobacteria biomass in Castle Lake, California with ice-out date occurring earlier in response to regional warming patterns (Park et al. 2004) or reduced productivity in Lake Tanganyika related to reduced vertical mixing and upwelling of nutrients related to sharpened density gradients as the lake warms and wind speeds decline (O'Reilly et al. 2003, Verburg et al. 2003)[1]. Perhaps the best documentation of the ecological effects of climate change on lakes comes from Lake Washington (e.g., Hampton et al. 2006a, Hampton 2005, Romare et al. 2005, Winder and Schindler 2004a, Winder and Schindler 2004b).

Table 1. Summary of published lake warming trends.

Lake	Location	Period	Warming Rate, $^{o}C\ yr^{-1}$	Basis [h]
Lake Tahoe[a]	Calif.-Nev.	1970-2002	0.015	VWA
Lake Washington[b]	Seattle, WA	1964-1998	0.026	VWA
Lake 239[c]	NW Ontario	1964-1998	0.108	DA
Lake Maggiore[d]	Italy	1963-1998	0.03	VWA
Lake Zurich[e]	Switzerland	1947-1998	0.016	VWA
Lake Tanganyika[f]	E. Africa	1913-1975 1975-2000	0.0042 0.0039	DA DA
Lake Malawi* [g] *(>300 m depth)	E. Africa	1939-1999	0.01	VWA

Adapted from Coats et al. (2006)
[a] Coats et al. (2006)
[b] Arhonditsis et al. (2004)
[c] Schindler et al. (1996)
[d] Ambrossetti and Barbanti (1999)
[e] Livingstone (2003)
[f] Verberg et al. (2003)
[g] Vollmer et al. (2005)
[h] VWA – Volume-weighted average; DA– Depth average

The largest lakes in the Seattle metropolitan area – Sammamish, Washington, and Union – have been the focus of King County's (formerly METRO's) Major Lakes water quality monitoring program (Major Lakes Program) since the late 1960s and early 1970s (e.g., King County 2005a, King County 2003a, King County 2002a, Tomlinson et al. 1977, Isaac et al. 1966). These lakes have also been the focus of a variety of investigations conducted by researchers at the University of Washington (e.g., Edmondson et al. 2003, Welch et al. 1986, Rattray and Shetye 1982). Routine water quality monitoring of Lake Washington by University of Washington (UW) researchers and of all three lakes by King County continues. In the last few years, more specific studies have focused on the movement and trophic interactions of salmonids and other fish species due to the use of these lakes by Endangered Species Act (ESA) listed species of salmon (e.g., Beauchamp et al. 2004).

This report describes the initial results of a field sampling program to collect continuous (15 minute frequency) temperature profile data in these lakes using a variety of equipment and

[1] But see Eschenbach (2004) for a critical review of the evidence presented by O'Reilly et al. (2003)

deployment methods. This sampling effort was initiated to provide temporal and spatial resolution of lake temperatures sufficient to evaluate the timing of spring stratification, development of diurnal thermoclines, the timing of lake turnover in the fall, data for coupling fish tracking thermistors with lake temperatures, and to support further hydrodynamic model testing and development. The monitoring equipment, approach, and goals are critically evaluated in this report and recommendations for changes to the current program are made.

1.1 Study Area

The study area covers the lakes monitored as part of King County's Major Lakes Monitoring Program – Lake Sammamish, Lake Washington, Lake Union, and the Lake Washington Ship Canal (Figure 1). Figure 1 also shows the locations of current and historical temperature monitoring locations, including stations routinely sampled as part of the ongoing Major Lakes Monitoring Program (King County 2005b), selected Remote Underwater Sampling System (RUSS) telemetered buoy profiler stations (now retired), selected Major Lakes Hydrodynamic Study stations (Schock 2002), and thermistor chains installed on the Lake Washington floating bridges as part of King County Wastewater Treatment Division Habitat Conservation Planning studies.

1.2 Project Background

Long term changes in the temperature dynamics of Lake Washington, including a trend of increasing temperatures, and related biological effects have been identified (e.g., Hampton et al. 2006a, Hampton 2005, Romare et al. 2005, Arhonditsis et al. 2004, Winder and Schindler 2004a, Winder and Schindler 2004b). Arhonditsis et al. (2004) estimated that the surface (0 – 10 m) and whole lake temperatures have increased over the period 1964-1998 by 1.5 ^{o}C (0.0458 ^{o}C yr^{-1}) and 0.98 ^{o}C (0.0268 ^{o}C yr^{-1}), respectively. This long-term trend was best described by a trend of increasing atmospheric long wave radiation – consistent with expectations from human-induced global climate warming (Arhonditsis et al. 2004). The warming trend has been greatest for the whole lake from April to September, for the epilimnion from August to October and for the hypolimnion in March and April (Arhonditsis et al. 2004). In addition to the overall long-term trend, there is a significant influence of the PDO, and to a lesser extent ENSO, on lake temperatures (Arhonditsis et al. 2004).

Winder and Schindler (2004b) showed that long-term lake warming trends have resulted in extension of the spring-summer stratification period by 25 days over the last 40 years (1962-2002) – mainly due to earlier initiation of spring stratification, which occurs about 16 days earlier than it did 40 years ago. Again, the influence of the PDO and to a lesser extent ENSO superimposes variability on the long-term trends in stratification onset and termination (Winder and Schindler 2004b). In response to earlier onset of stratification, the spring phytoplankton bloom occurs about 19 days earlier than it did in 1962. Winder and Schindler (2005a) have suggested that this might be a factor in an observed decline in *Daphnia* abundance (the main consumers of the spring phytoplankton bloom), with implications for food supply to upper trophic levels in the lake. The timing of the spring peaks of two species of *Daphnia* (*D. pulicaria* and *D. thorata*) are also undergoing complex phenological shifts, with implications for sockeye salmon fry specifically and other zooplankton and planktivores in general (Hampton et al. 2006a).

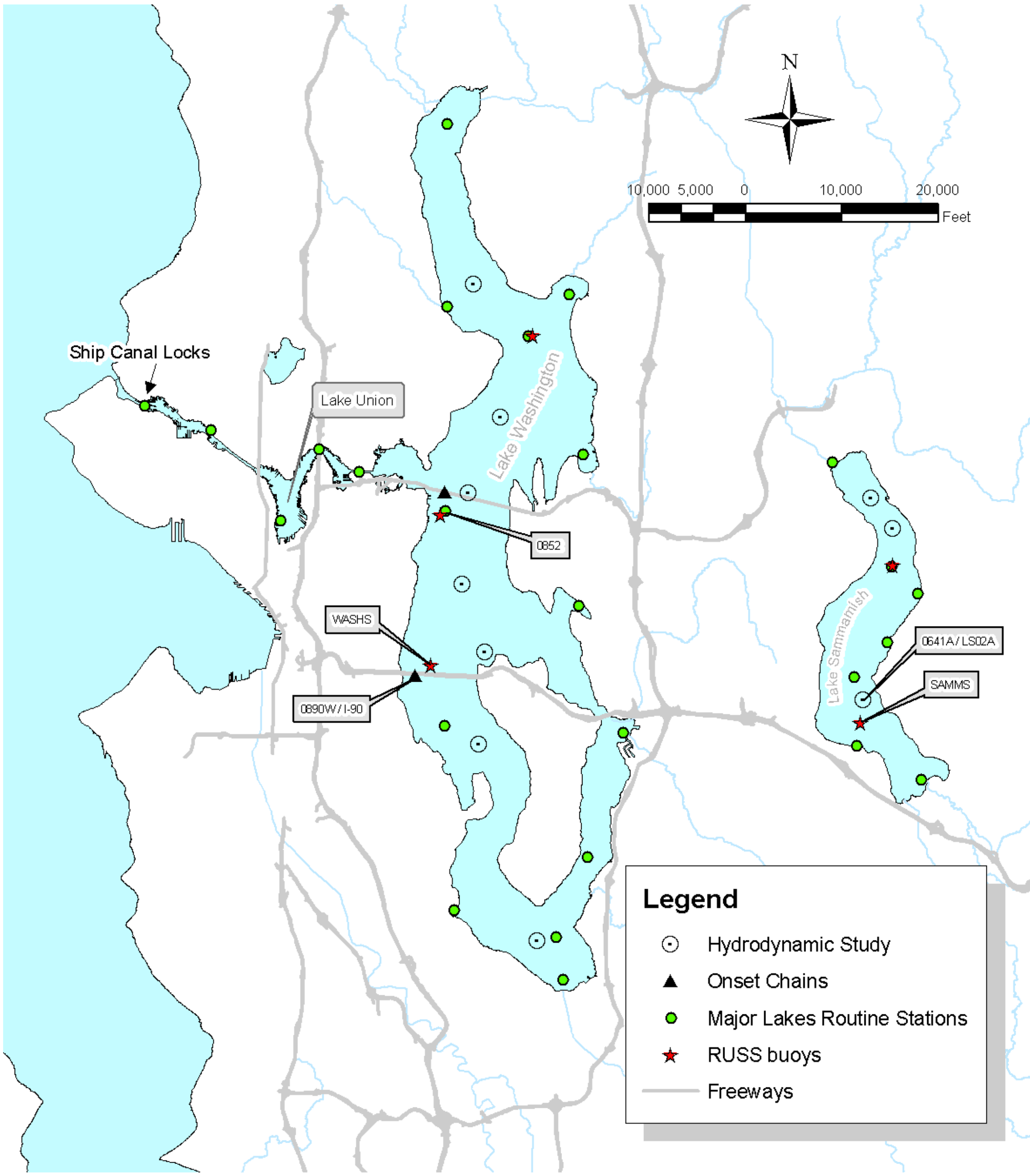


Figure 1. Major Lakes Program study area, including routine monitoring locations.

Edmondson et al. (2003) hypothesized that the progressive warming of Lake Washington in recent years may be leading to more physically stable conditions during summer that provide a competitive advantage to *Microcystis*, a blue-green alga or cyanobacterium, which can regulate its buoyancy (Figure 2). This blue-green species is capable of producing neurotoxins and hepatotoxins, with implications for the health of humans and other animals exposed directly through ingestion of water or indirectly via dermal contact (Chorus et al. 2000).

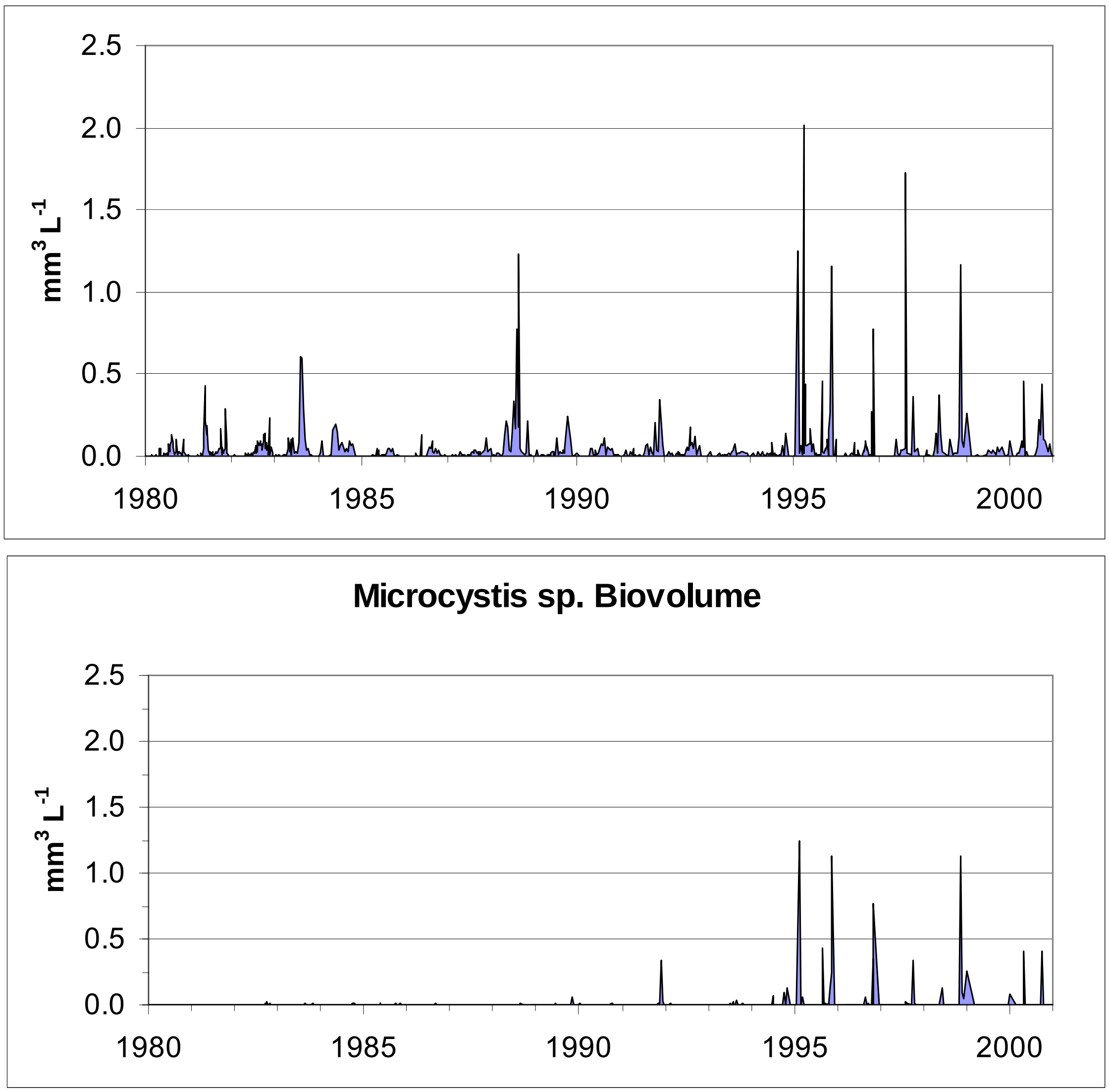


Figure 2. Biovolumes of total cyanobacteria (top) and *Microcystis spp.* (bottom) in Lake Washington, 1980-2001.

Rising lake temperatures have also been suggested as a possible explanation for the loss of adult sockeye salmon as they migrate through Lake Washington in recent years (Stifler, L., Seattle Post-Intelligencer, July 11, 2005; Cornwall, W., Seattle Times, June 22, 2005). Elevated water temperature in general has been identified as a potentially significant factor in the decline of ESA-listed salmon (Kerwin 2001), although this concern is related more specifically to temperature increases in local streams resulting from clearing of shading vegetation, channel and wetland modifications, and water diversions.

King County is also currently developing hydrodynamic and water quality models of these lakes as part of the County's Freshwater Program. One goal of this modeling effort is the simulation of temperature dynamics in these lakes and coupling of the hydrodynamic model to a water quality model. These models have been developed in part to evaluate future lake temperature and water quality conditions in response to climate change.

Of particular relevance to the continuous temperature monitoring effort described in this report are radio and thermistor tagging studies designed to track adult Chinook and sockeye salmon migration through Lake Washington (e.g., Newell and Quinn 2005). During these studies, Chinook (Seattle-District ACOE in 2005 and 2006) and sockeye (UW in 2002 and 2003, and Muckleshoot Indian Tribe in 2006) were equipped with acoustic tags and temperature sensors to evaluate their thermal exposure and temperature/depth preferences while migrating through the lake (H. Berge, King County Water and Land Resources Division, pers. comm.).

1.3 Goals and Objectives

The study approach is designed to provide adequate spatial and temporal resolution of continuous temperature data to evaluate the timing of spring stratification, development of diurnal thermoclines, the timing of lake turnover in the fall, for coupling fish tracking thermistors with lake temperatures, and to support further hydrodynamic model testing and development. The collection of additional temperature data described in this report should aid in our understanding of the roles of natural climate variability, human-induced climate trends, and other anthropogenic effects on lake temperature specifically and water quality in general. For example, the increased frequency of blue-green algal blooms may be due more to climate change (natural and human-induced) than to increased nutrient inputs resulting from urbanization of the lake drainage basins. These temperature data will also supplement the routine temperature profiling data collected by King County and the UW and data collected in the Ship Canal by the Seattle-District Army Corps of Engineers.

1.4 Historical Data Review

Historically, temperature data have been collected on a weekly, bi-weekly, or monthly basis at one or more locations within each lake. A single profile is conducted at a particular location, typically near mid-day, by lowering a recording thermistor to specific depths. More recently, attempts have been made to record temperature profiles at a number of locations in Lakes Washington and Sammamish using Remote Underwater Sampling Station (RUSS) profilers (maximum of 4 profiles per day at 1 m depth intervals) and strings of continuous temperature sensors deployed from the Lake Washington floating bridges (hourly at 2, 7, 10, 15, 20, 25, 35 and 55 m depths) or suspended from the lake bottom (minimum of 3 minutes at 1 m intervals spanning approximately 3 to 26 m depth or every 8 minutes at 1 m intervals from 3 m to the bottom) (King County unpublished data). The locations where long-term routine profiles and recent continuous data have been collected are shown in Figure 1. Example data sets for each sampling approach are shown in Figure 3.

Each of these approaches to the collection of temperature data has advantages and disadvantages. Routine profiling is a reliable means of collecting temperature data (see Figure 3A), but the temporal resolution (currently 2 profiles per month between March and October and 1 per month between November and February) does not provide precise information on the timing of stratification and destratification and practically no information regarding higher frequency temperature fluctuations that occur due to internal waves (seiches) that occur on a daily or sub-daily frequency.

The RUSS system was plagued by vandalism and maintenance problems, due to its high visibility as well as its technical complexity required for system operations that include solar battery charging and onboard computer and telecommunications equipment. When operational, the RUSS was capable of collecting temperature, dissolved oxygen, pH, specific conductance and *in situ* chlorophyll fluorescence data over nearly the entire water column. The sampling frequency of up to 4 times per day captured some of the diel changes in temperature (and other parameters) due to internal waves and the development of diurnal thermoclines (see Figure 3B). A major advantage of the RUSS was the ability to telemeter data from the buoy to a centralized database in near real-time, allowing for the application of automated web-based display of data and e-mail alerts when specified sampling or data conditions were not met. The last operating RUSS – SAMMS on Lake Sammamish – conducted its last profile on September 24, 2005.

The Onset™ thermistors that have been used on the floating bridges and a few Major Lakes Hydrodynamic Study locations (see below) are relatively inexpensive and reliable. However, these devices require field personnel to occasionally download each thermistor, which can create some difficulties with data file retrieval, tracking, and processing. These instruments have been typically set up to measure temperature at hourly intervals or less. This sampling frequency captures much of the diel temperature variation, but in some cases some vertical resolution has been sacrificed (see Figure 3C).

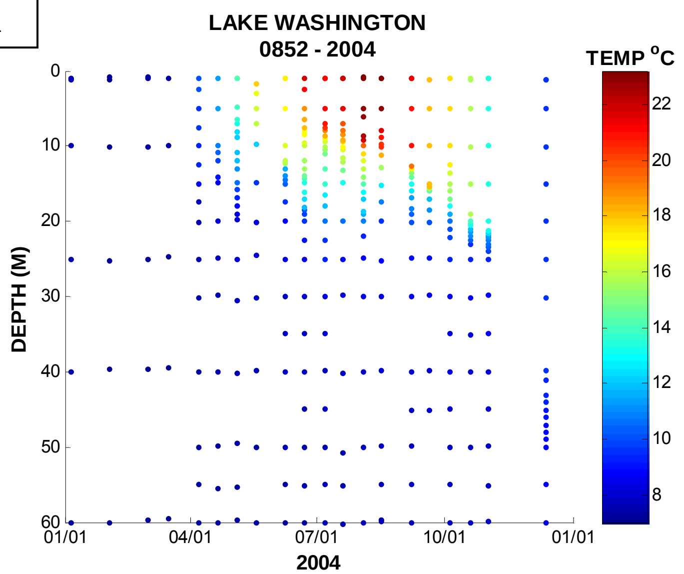
Bottom-deployed thermistor chains [Richard Brancker Research (RBR) XR-420-T24] were purchased for use in the Major Lakes Hydrodynamic Study of Lake Washington and Sammamish (Schock 2002). An example of RBR data collected in 2004 from a mid-lake location in Lake Sammamish (0641A/LS02A) as part of the Major Lakes Hydrodynamic Study is shown in Figure 3D.

The major advantage of the RBR thermistors is that they can be extremely accurate when calibrated (±0.002 ^{o}C) compared to ±0.2 ^{o}C typical of the various Onset HOBO Water Temp Pro thermistors), have very accurate internal clocks (± minute yr^{-1} compared to ±1 minute mo^{-1} for the Onset thermistors), rapid response time (~3 seconds compared to 5 minutes for the Onset thermistors) and data are downloaded simultaneously from all thermistors to a single data file.

These data files still require transfer to office computers and file tracking and processing to produce usable data.

One major disadvantage is that the chains purchased for the Major Lakes Hydrodynamic Study are only 24 m long. Therefore, sampling at every depth in the deeper parts of Lake Washington (maximum depth of 65 m) can only be accomplished by deploying two offset chains at the deepest locations. A second disadvantage is that the manufacturer recommends annual calibration of the thermistor chain. Annual calibration was not required in the Sampling and Analysis Plan (SAP) for the Major Lakes Hydrodynamic Study and no study report was produced as part of that study that might have established the need for routine calibration and maintenance of the RBR chains. Financial resources were insufficient to cover the costs of calibration/maintenance (~$1,500 per chain) of all of the existing RBR chains as part of the study reported here, although funds were found to refurbish and calibrate 2 chains that were subsequently deployed at the mid-lake locations in Sammamish and Washington in 2006. Based on the results presented below, it appears that at a minimum, calibration/maintenance of the thermistor chains should be performed on an annual basis.

A



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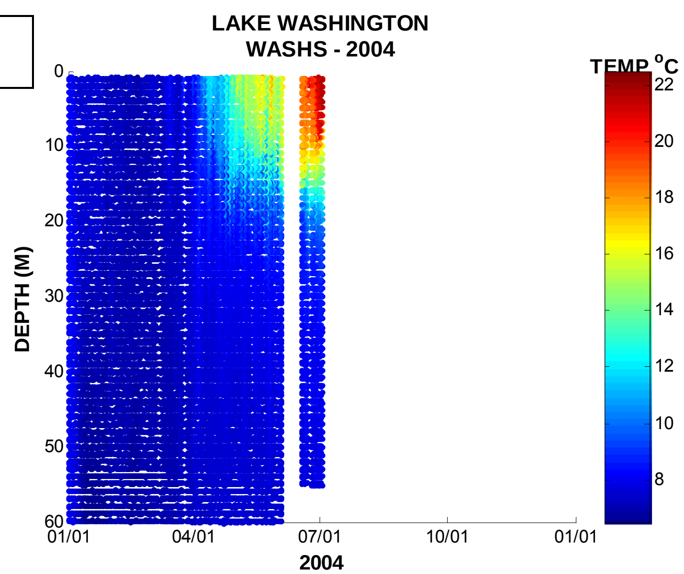

Figure 3. Example temperature data sets for (A) routine temperature profiling at Lake Washington 0852, (B) RUSS buoy WASHS on Lake Washington, (C) Onset thermistor chain on Lake Washington I-90 floating bridge, and (D) RBR thermistor chain at Lake Sammamish 0641A (LS02A).

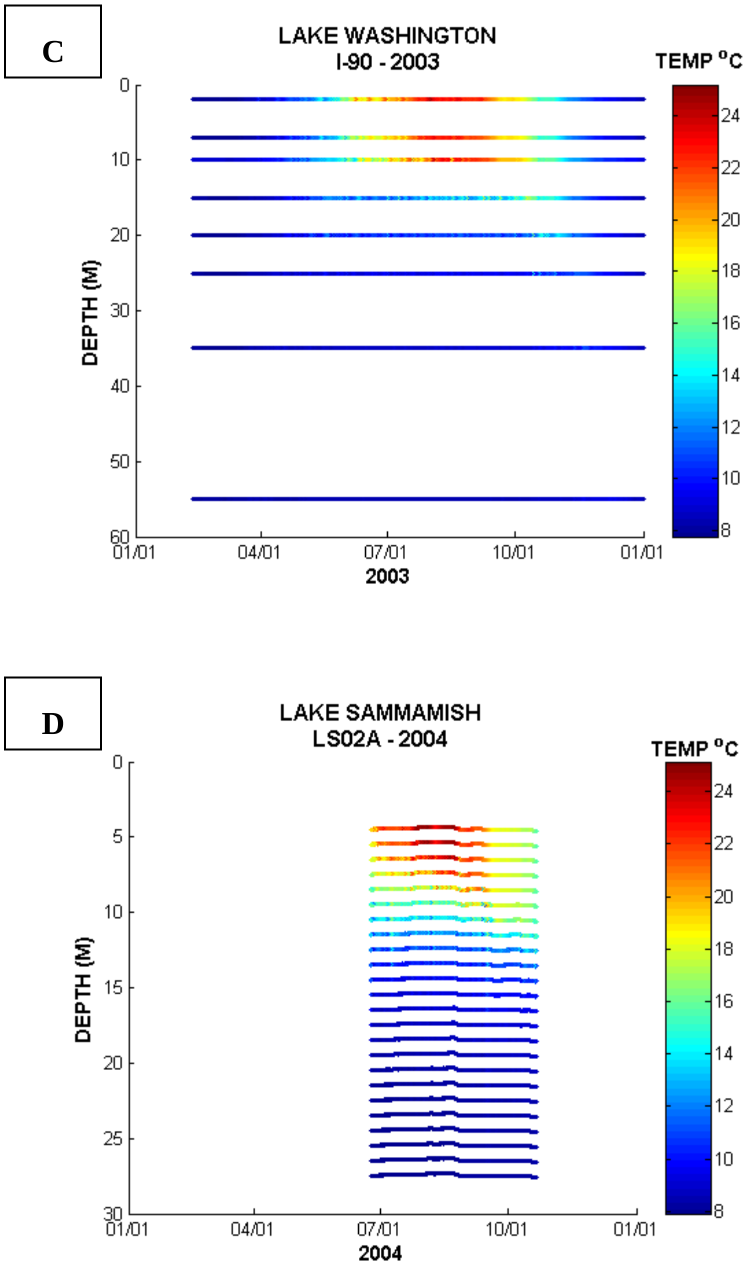

Figure 3 (continued). Example temperature data sets for (A) routine temperature profiling at Lake Washington 0852, (B) RUSS buoy WASHS on Lake Washington, (C) Onset thermistor chain on Lake Washington I-90 floating bridge, and (D) RBR thermistor chain at Lake Sammamish 0641A (LS02A).

2.0. METHODS

The study methods are briefly summarized below. The interested reader is referred to the Sampling and Analysis Plan (SAP) for further details (King County 2005c).

2.1 Field Study

Field instrumentation used in this study and their factory specifications are provided in Table 2. In general, there were 2 types of deployments. The first type of chain was previously purchased from Richard Brancker Research (RBR) for use in the Major Lakes Hydrodynamic Study (Schock 2002) and consisted of a multichannel data recorder and 24 thermistors arranged 1-m apart below the data logger (model XR-420-T24). A pressure transducer (model DR-1050) was also attached to the logger housing to provide information about the depth of the logger. The RBR chains were suspended from the bottom of the lake (Figure 4). The second type of chain was created by King County Environmental Laboratory staff by attaching Onset HOBO Water Temp Pro (Version 1) thermistors to a weighted nylon line and suspending them from various platforms floating in the lake including bridges, docks, and buoys (Figure 5).

Table 2. Summary of instrument precision, accuracy and response time

Instrument	Range	Accuracy	Resolution	Response Time
Richard Brancker Research (RBR)				
Thermistor (XR-420-T24)	-5 to 35 ^{o}C	±0.002 ^{o}C	<0.00005 ^{o}C	< 3 seconds
Pressure Sensor (DR-1050)	Up to 740 m	±0.05% full scale	<0.001% full scale	10 milliseconds
Onset				
HOBO Water Temp Pro (Version 1)	0 to 50 ^{o}C	±0.2 ^{o}C 0-50 ^{o}C	0.02 ^{o}C @ 25 ^{o}C	5 min to 90%
Additional Notes: **RBR XR-420:** replaceable battery, operating depth 740 m, 4 MB flash memory **RBR DR-1050:** replaceable battery, operating depth 740 m, 4 MB flash memory **HOBO Water Temp Pro:** replaceable battery, 21,580 measurement capacity, time accuracy ±1 minute per month, waterproof to 400 ft.				

Ten stations were occupied or established for this study – 2 in Lake Sammamish, 6 in Lake Washington, 1 in Lake Union and 1 at the Ship Canal Locks (see Table 3 and Figure 6). Stations equipped with RBR X-420-T24 thermistor chains were located along the main axis of Lake Washington to provide longitudinal resolution of temperature dynamics (Figure 1). The deployment of RBR X-420 thermistor chains at one location in Lake Sammamish was intended to characterize the high frequency temperature dynamics of this lake (Figure 1). A vertical resolution of 1 m was selected to characterize the vertical temperature dynamics of these lakes. Due to the limitations of the existing RBR equipment, the available RBR thermistor chains only provided data for 24 m of the water column. The portion of the water column that was sampled by these thermistor chains covered depths from approximately 3 to 26 m below the water surface. The RBR deployment design is presented in Figure 4. Each thermistor chain was equipped with an RBR pressure transducer (DR-1050) so that the depth of each thermistor during each deployment could be determined.

At the northern and southern RBR stations in Lake Washington and in Lake Sammamish, the RBR chains covered approximately 60 (0804A/NWASH) to 80 (0641A/LS02A) percent of the water column; focused on the depths that encompass the location of the seasonal thermocline. At the proposed mid-lake Lake Washington RBR station (0861A/MIDWAY), a single chain covered the seasonal thermocline, but missed some of the more subtle temperature dynamics in the deeper water column.

RBR thermistors were set up to record instantaneous temperature at 15-minute intervals[2] and the pressure transducer was set to record instantaneous depth at hourly frequency. Memory and battery life allowed data to be retrieved on approximately a 6 month schedule. This schedule presented the risk of loosing up to 6 months of data at any location, but more frequent retrieval of equipment and data would have excessively increased the level of effort beyond that already allocated for the Major Lakes Monitoring Program.

An Onset™ thermistor chain was deployed from each floating bridge (SR-520 and I-90[3]) on Lake Washington and from a dock at a relatively deep location on the south end of Lake Union that provided high frequency sampling data from near the water surface to the bottom (Figure 5). On the Lake Washington floating bridges, thermistors were attached on July 28, 2005 (0890E) and August 9, 2005 (0852B) to a line at fixed depths – initially 2, 4, 6, 8, 10, 12, 15, 20, 25, 30, 35, and 55 m below the water surface. However, additional resources became available that allowed addition of thermistors on September 20, 2005 at 14, 16, and 18 m (the sensor at 15 m was moved to one of these depths), which provided better resolution of the seasonal thermocline. The Lake Union station thermistor chain was attached to a dock on March 29, 2006, with

[2] The Lake Sammamish chain at 0641A (LS02A) was an exception, which remained on the 10-minute interval sampling frequency established for the Major Lake Hydrodynamic Study (Schock 2002) until June 6, 2006.

[3] A second chain was deployed on the I-90 floating bridge on August 9, 2005 as a backup and to collect data in a more central location, rather than in the vicinity of the thermistor chains deployed previously by Doug Houck as part of the King County Wastewater Treatment Division's Habitat Conservation Plan.

Table 3. Thermistor chain deployment locations.

Locator (Station)[a]	Water Depth	Northing/Easting [d]	Equipment [e]	# of Sensors
Lake Sammamish				
0641A (LS02A) [b]	30	215863 / 1329893	RBR	24
SAMMS / RUSS [b,c]	30	213515 / 1329640	Onset	11
Lake Washington				
0804A (NWASH) [b]	40	265514 / 1287012	RBR	24
0852B (SR-520)	60	237499 / 1286500	Onset	12 [f]
0861A (MIDWAY) [b]	55	227896 / 1288438	RBR	24
0890W (I-90W)	55	218442 / 1283479	Onset	12 [f]
0890E (I-90E)	55	218361 / 1285261	Onset	12 [f]
0831A (SWASH) [b]	28	190872 / 1296115	RBR	24
Lake Union				
0522B (SUNION)	14	234567 / 1269291	Onset	7 [f]
0512B (Large Lock)	13	246506 / 1255828	Onset	8 [f]

[a] King County Laboratory Information System (LIMS) station Locator and original station name. The LIMS Locator will be used in LIMS to store other water quality data collected at these stations.

[b] This station was previously established as part of the King County Major Lakes Hydrodynamic Study (Schock 2002).

[c] SAMMS Remote Underwater Sampling Station (RUSS) buoy does not have a proposed LIMS Locator.

[d] Northing/Easting are in State Plane feet, Washington North, NAD83/91 (HPGN). It is expected that the exact location of each deployment was within a 30 m radius of these station coordinates due to limitations of wind and wave conditions and deployment logistics.

[e] Sampling frequency was 15 minutes recorded on the quarter hour. RDR pressure transducer sampling frequency was hourly.

[f] Thermistor depths for the Onset chains deployed on each bridge and the SAMMS RUSS buoy are 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 25 (maximum depth for SAMMS RUSS), 30, 35 and 50 m. Depths for the Onset chain suspended from a dock in the southern end of Lake Union near station A522 are 2, 4, 6, 8, 10, 12, and 14 m. The Onset chain currently deployed at the Hiram M. Chittenden Locks has 8 thermistors suspended from a float at 2, 5, 7, 9, 10, 11, 12, and 13 m water depth.

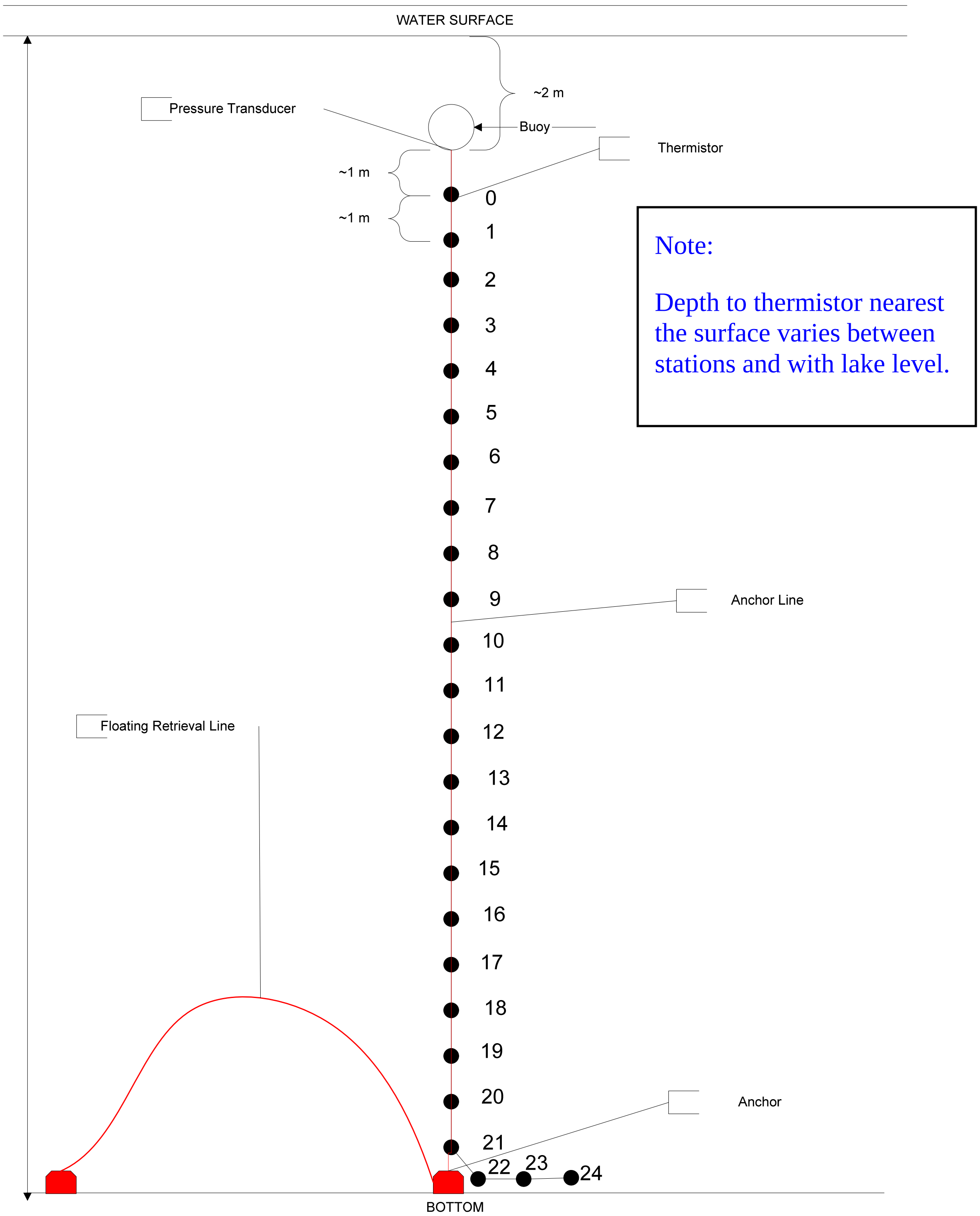

Figure 4. RBR thermistor chain deployment design.

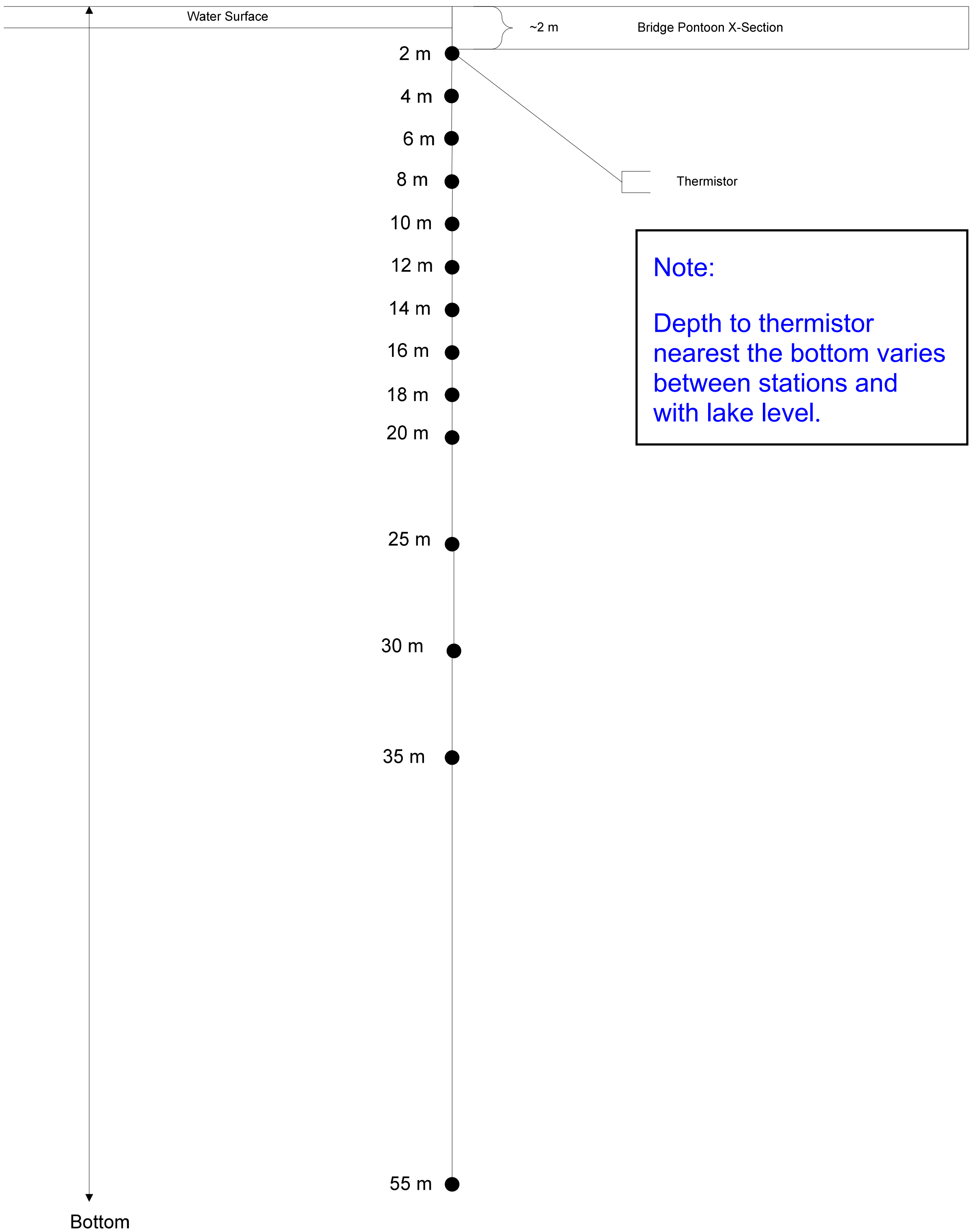

Figure 5. Lake Washington floating bridge Onset thermistor chain design.

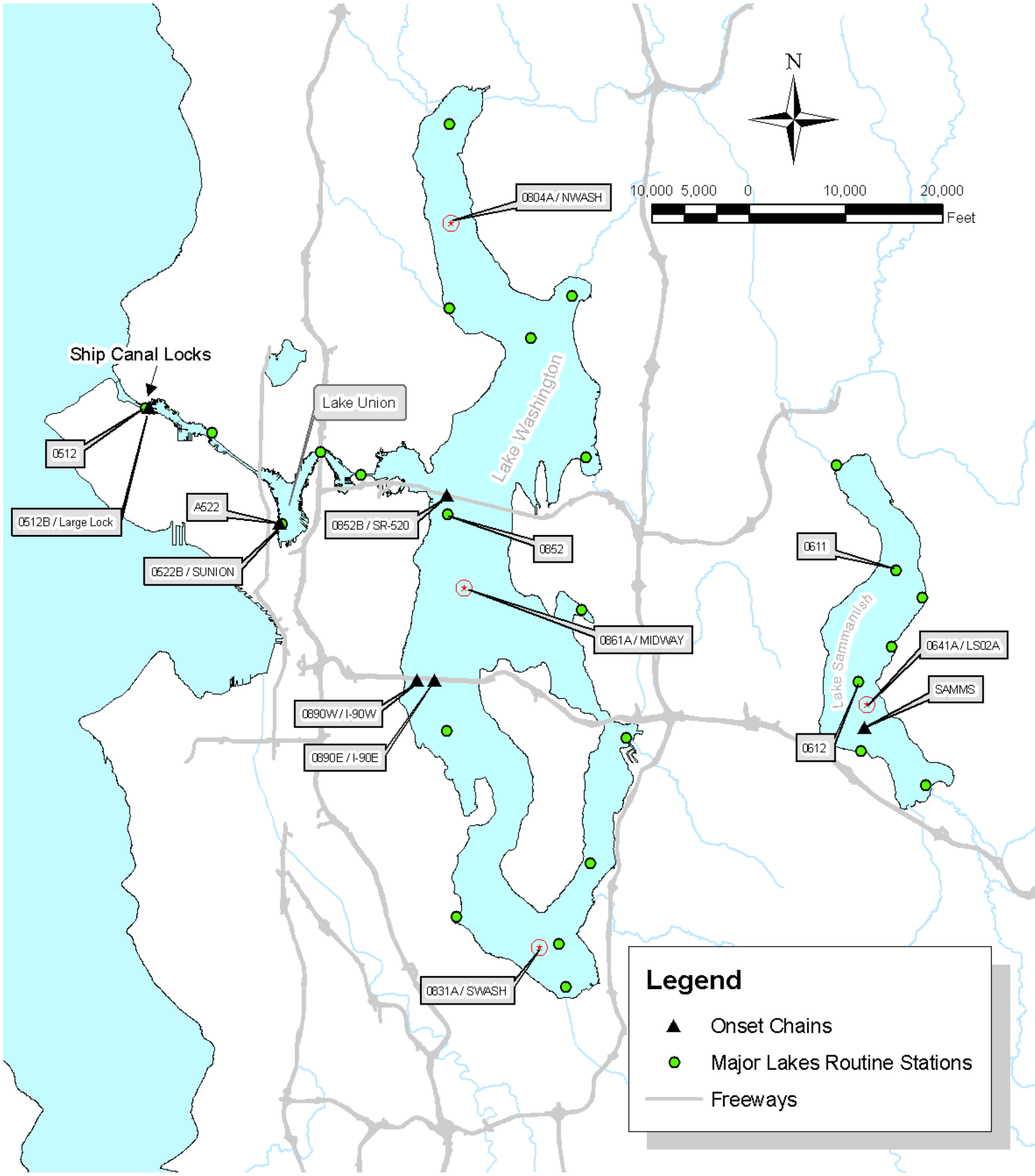

Figure 6. RBR and Onset thermistor chain deployment locations.

Note: Locations of the two RUSS buoys remaining in mid-2005 are also shown, but these buoys are no longer operational and have been removed from the lake.

thermistors at fixed depths of 2, 4, 6, 8, 10, 12, and 14 m. The Onset bridge thermistor chain deployment design is presented in Figure 5. An Onset thermistor chain already deployed at the Hiram M. Chittenden Locks on April 28, 2004 (at fixed depths from 2, 5, 7, 9, 10, 11, 12 and 13 m below the water surface) was incorporated into this study (Figure 6). An Onset thermistor chain was attached to the SAMMS RUSS buoy platform on May 17, 2006. However, this platform was replaced with a trial buoy profiling system so the chain was redeployed with the RBR chain at the 0641A (LS02A) site on August 10, 2006.

2.2 Data Processing and Analysis

All computers used to synchronize thermistor clocks were logged into the network and synchronized with local network time in the morning prior to launching and setting thermistors and pressure transducer clocks. The computer time was also checked against atomic clock time to verify that the computer clock displayed the correct local time. Therefore, temperature time series data were recorded in Pacific Daylight Time (PDT) or Pacific Standard Time (PST) depending on the time of deployment. Downloaded data were processed to convert the data recorded in PDT or PST to Coordinated Universal Time (UTC) prior to loading the data into a SQLServer database. The processed data meeting Quality Control (QC) criteria are available to the public through King County's Hydrologic Information Center website (http://dnr.metrokc.gov/wlr/waterres/hydrology/GaugeSelect.aspx).

While the thermistor chains attached to the bridges, docks, and surface buoys were at fixed depths, determination of the RBR thermistor depths was complicated by the fact that the thermistors were suspended from the bottom so that the depth of each RBR thermistor was dependent on the elevation of the water surface relative to each thermistor. Pressure transducers attached to the data logger (which was attached directly to a submerged float – see Figure 4) provided a time series with which to estimate the depth of the thermistors. Based on atmospheric pressure recorded at the UW located just west of Lake Washington, and the temperature recorded at the upper most thermistor, the depth of the thermistor at any given point in time was calculated using the following formula:

$$z = \frac{P_{RBR} - P_{atm}}{g\ \rho(t)}$$

Where,

z	=	depth in meters (m)
P_{RBR}	=	Pressure recorded by RBR in Pascals (Pa, N m^{-2} or kg m^{-2} s^{-2})
P_{Atm}	=	Atmospheric pressure (UW) in Pa
g	=	acceleration due to gravity (9.80665 m sec^{-2})
$\rho(t)$	=	density of water at ambient temperature (kg m^{-3})

Incorporation of a time-varying atmospheric pressure correction resulted in much more accurate thermistor depth estimates than those obtained using a constant atmospheric pressure correction. The estimated depths were also consistent with observed water surface elevation changes in the lakes (e.g., Figure 7).

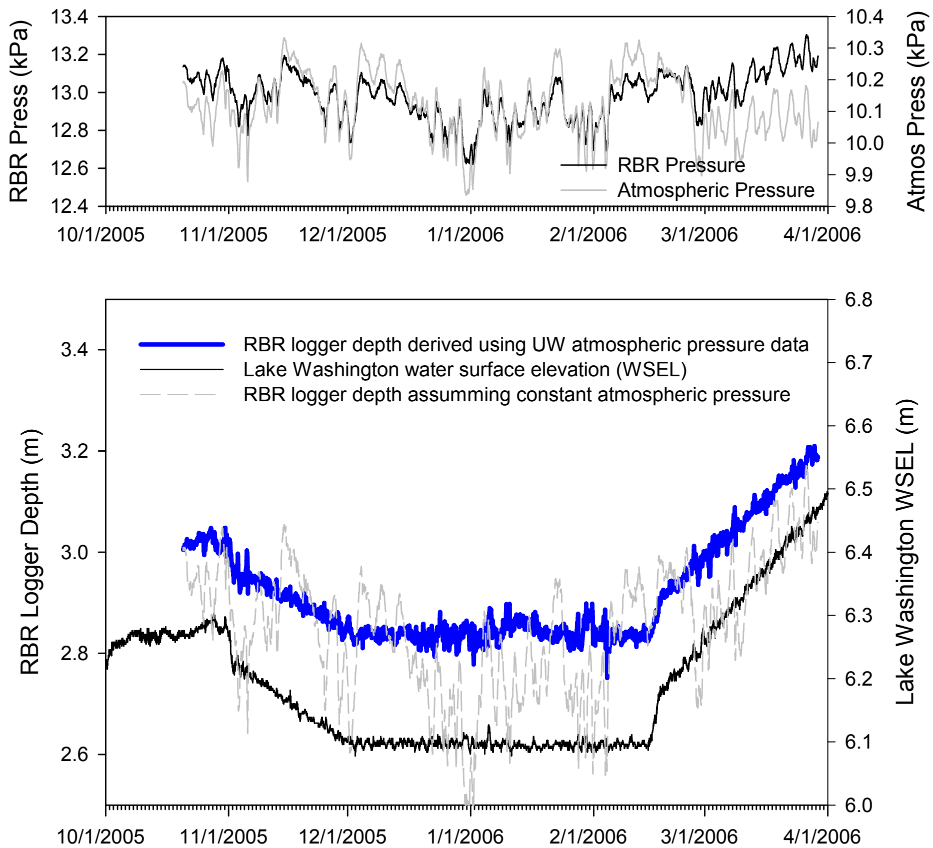

Figure 7. Example of processing pressure transducer data into estimates of RBR logger depth – 0831A (SWASH) October 2005 to March 2006.

Unfortunately, the pressure transducers routinely failed to record data for more than a few weeks. If a complete record was available from another chain on Lake Washington, an average offset was calculated and the complete record with the offset was used to fill in missing data at another station. When no other pressure transducer record was available, the initial record was used to calculate the depth of the logger and then an offset from recorded lake water surface elevations were used to fill in the missing depths. It might have been easier to always estimate the elevation of the logger from the depth derived from the initial pressure recording and reported lake water surface elevation on the date of deployment, but it is suspected that on occasion the chain is not perpendicular to the lake bottom but is deflected downward by strong surface currents generated during strong wind storms (K. Schock, King County Wastewater Treatment Division, pers. comm.).

3.0. RESULTS AND DISCUSSION

3.1 Deployment History

3.1.1 Onset

Deployment history for the Onset HOBO Water Temp Pro thermistors is summarized in Figure 8. Continuous temperature monitoring conducted in Lake Washington as part of the study described in this report began in late July/early August of 2005. The Onset thermistor chain deployed in Lake Union wasn't established until March 2006 due to difficulties securing access to the private dock selected as the deployment location. The establishment of an Onset chain in Lake Sammamish did not occur until May 2006. The thermistors at the Ballard Locks were initially installed in April 2004 by Doug Houck, King County Wastewater Treatment Division. These data have also been loaded into King County's Hydrologic Information Center database (http://dnr.metrokc.gov/wlr/waterres/hydrology/GaugeSelect.aspx). All thermistor chains are functioning and have been redeployed in August 2006 and will be retrieved and downloaded in the next 6 months. Four thermistors have failed to record data or could not be downloaded resulting in lost data for that depth/period. Defective thermistors were returned to the manufacturer and replaced with working thermistors. Daily average data collected at each location are summarized in Figure 9 through Figure 14.

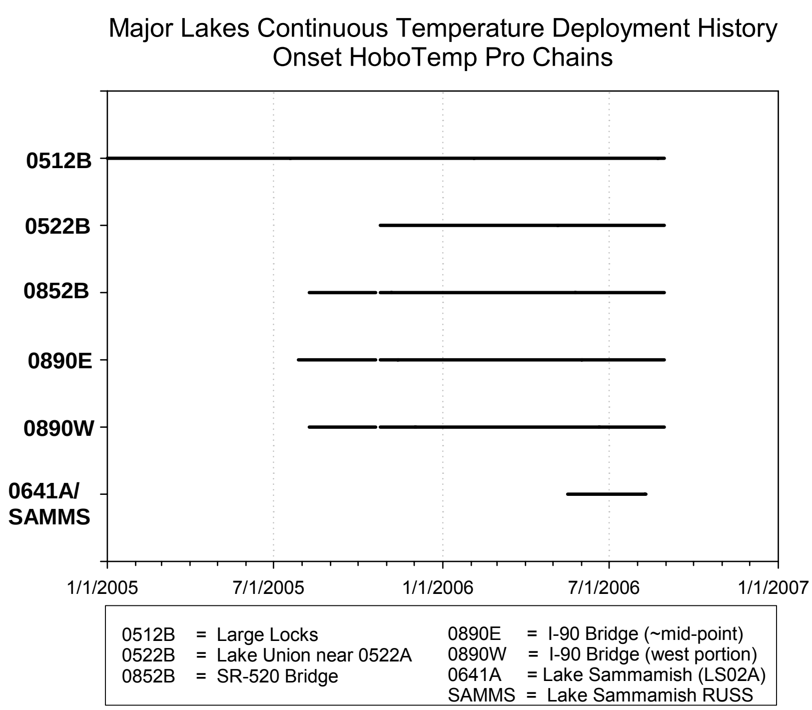

Figure 8. Major Lakes Onset HoboTemp Pro continuous temperature deployment history, 2005-2006.

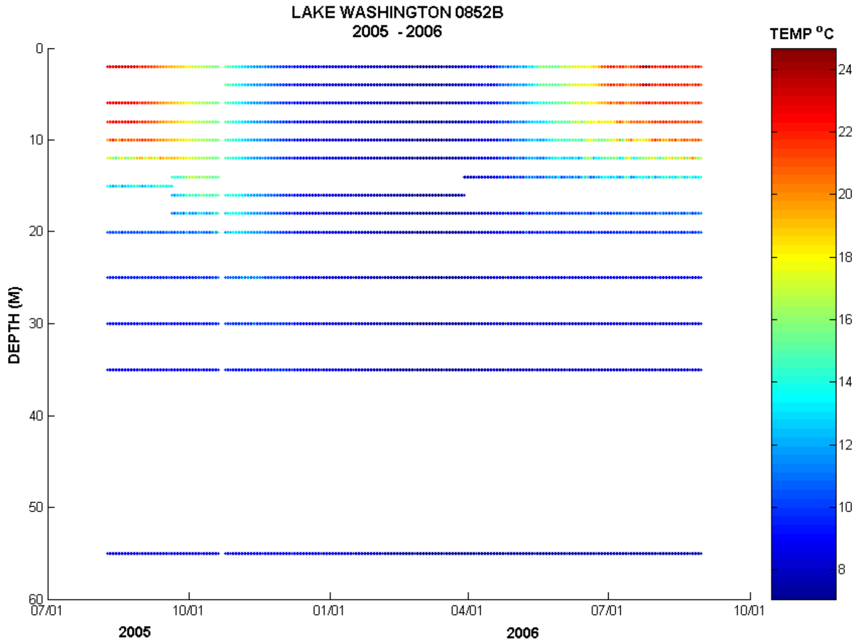

Figure 9. Major Lakes Onset HoboTemp Pro data summary for Lake Washington 0852B.

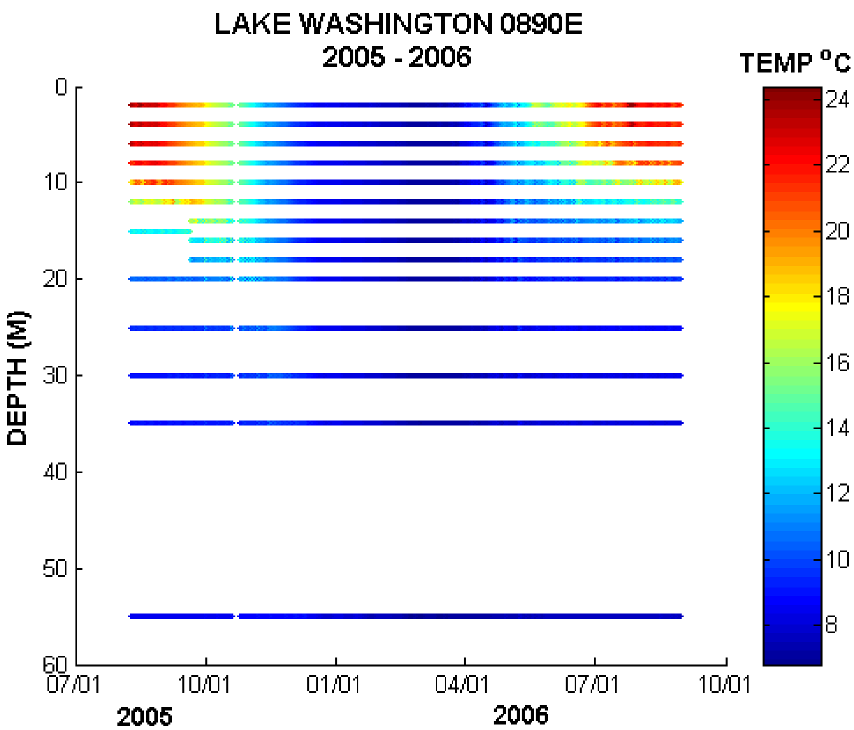

Figure 10. Major Lakes Onset HoboTemp Pro data summary for Lake Washington 0890E.

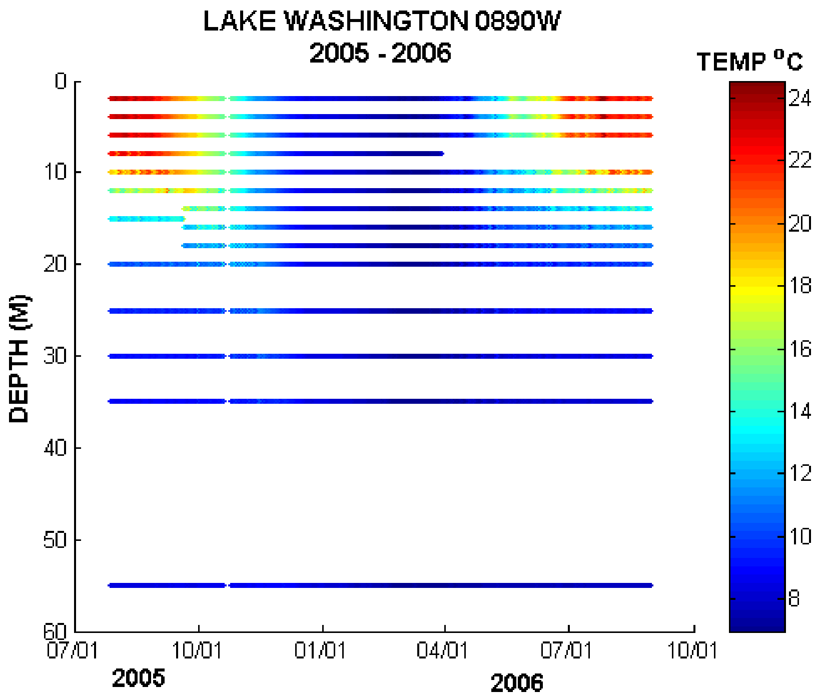

Figure 11. Major Lakes Onset HoboTemp Pro data summary for Lake Washington 0890W.

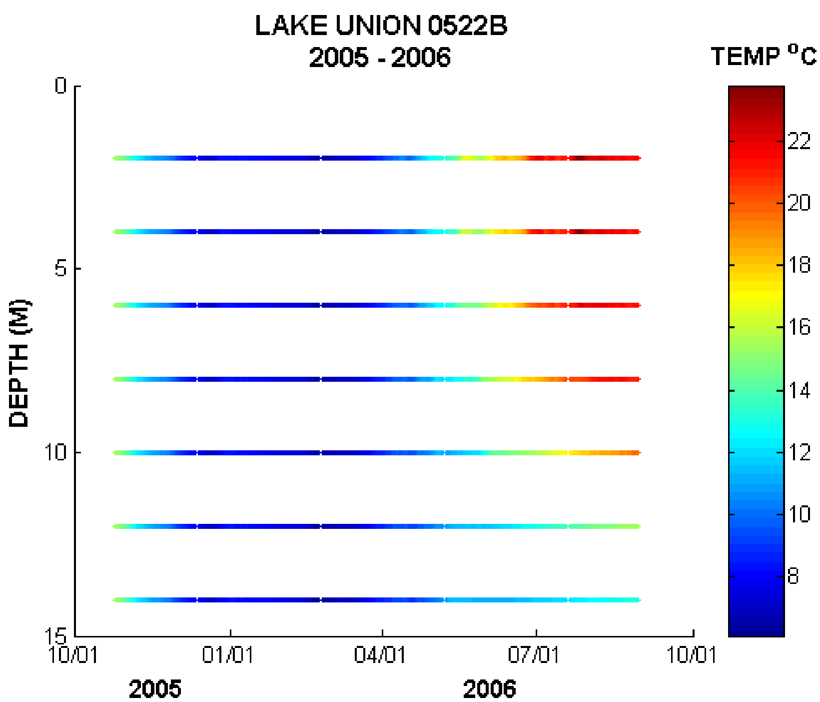

Figure 12. Major Lakes Onset HoboTemp Pro data summary for Lake Union 0522B.

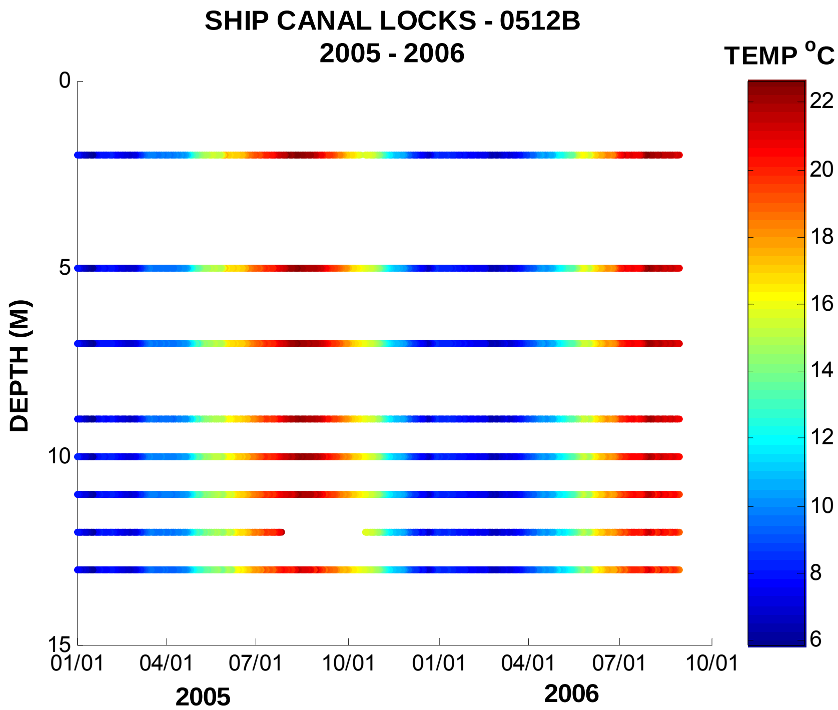

Figure 13. Major Lakes Onset HoboTemp Pro data summary for Ship Canal Locks 0512B.

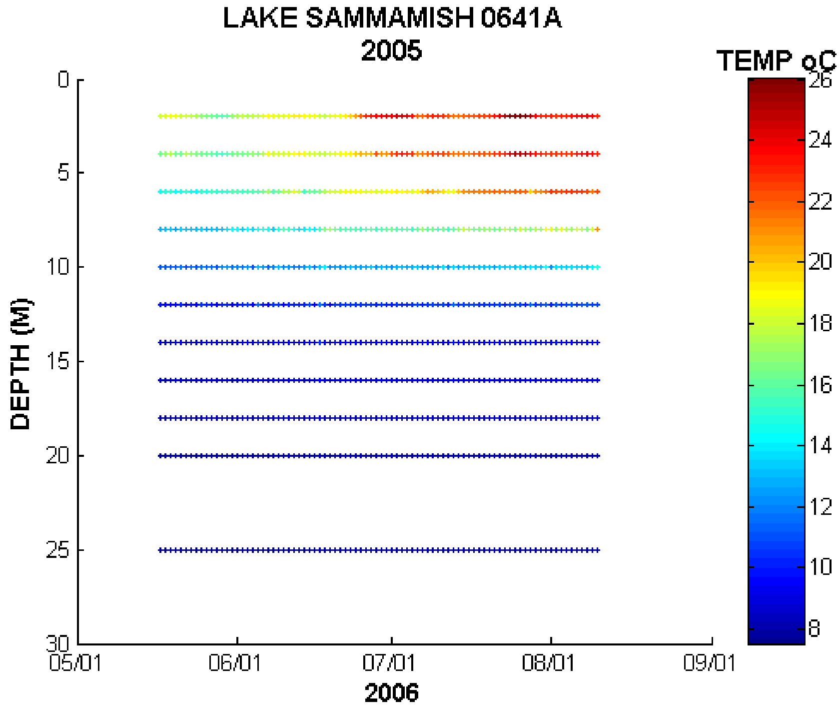

Figure 14. Major Lakes Onset HoboTemp Pro data summary for Lake Sammamish 0641A (LS02A).

3.1.2 RBR

The deployment history for the RBR thermistor chains is summarized in Figure 15. A thermistor chain was previously deployed in Lake Sammamish at station 0641A (LS02A) since March 2003 as part of the Major Lakes Hydrodynamic Study (Schock 2002). The RBR deployments at the locations in Lake Washington conducted as part of this study were initiated in August 2005. Prior to this study, deployments were made at these and several other locations for various durations as part of the Major Lakes Hydrodynamic Study (Schock 2002). A number of difficulties were encountered during deployments, including the problems associated with the pressure transducers mentioned above. During the first deployment at 0861A (MIDWAY), the submerged buoy was punctured (probably by a boat propeller) and the chain sank to the bottom. The chain was recovered and redeployed in September 2006. The chain deployed at 0831A (SWASH) in March 2006 has not been recovered and is presumed to have sunk to the bottom or to have been removed. It is unclear if the remaining RBR thermistor chains are in full working order (see Thermistor Calibration Check section below); one chain remains at 0641A in Lake Sammamish and two remain in Lake Washington (0861A/MIDWAY; 0804A/NWASH).

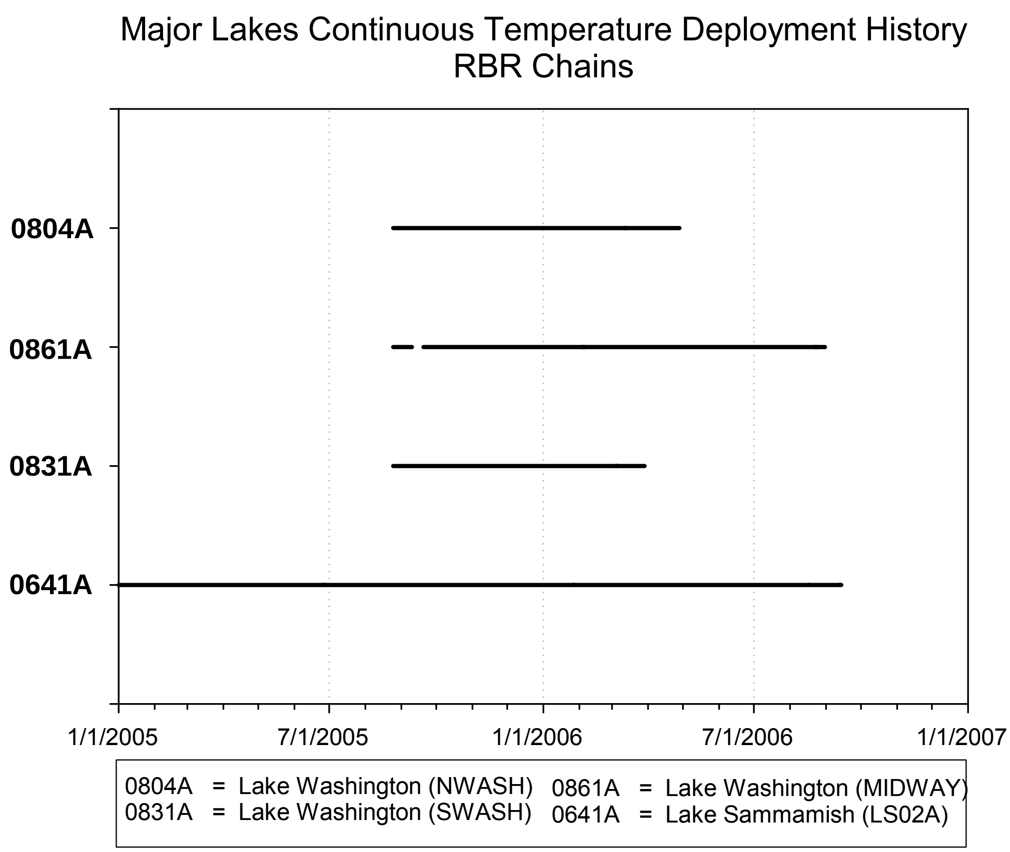

Figure 15. Major Lakes RBR continuous temperature deployment history, 2005-2006.

3.2 Thermistor Calibration Check

Thermistor chains were checked in the field during relatively isothermal conditions in late January and early February 2006 to evaluate potential bias or accuracy problems. This was accomplished by conducting profiles at 1-m intervals from surface to bottom at each thermistor chain location using profiling sondes deployed as part of the routine Major Lakes sampling program (currently a Sea-Bird CTD and Hydrolab Datasonde in Lake Washington/Union and a Hydrolab Datasonde in Lake Sammamish)[4]. Comparison of the profiler thermistor records to the thermistor chain data allowed for an assessment of thermistor accuracy and drift. The quality control criteria established in the Sampling and Analysis Plan stated that if recorded profiler temperatures differed by more than 0.2 ^{o}C from the temperature measured by a particular thermistor in the chain, the RBR thermistor chain or Onset thermistor probe would be replaced with available equipment from the backup equipment pool and the defective equipment returned for maintenance, calibration, or replacement if under warranty or if funds were available for repair (King County 2005c).

3.2.1 Onset Calibration Check

Hydrolab profiles were conducted specifically for calibration checks in the vicinity of the Lake Washington floating bridges (0852B and 0890E/0890W) on January 24, 2006 (Figure 16). Comparison to the Onset Hobo Water Temp Pro thermistor records for approximately the same time of day indicate that these thermistors were performing within the specified criterion of ±0.2 ^{o}C, with the exception of one thermistor at the bottom (55-m depth) of the 0890E (I-90E) chain. Nonetheless, there appears to be a relatively consistent positive bias when compared to the Hydrolab profile and differences between thermistors and Hydrolab measurements at the surface and bottom were at the maximum acceptable limit (0.2 ^{o}C).

At least for the surface thermistors, some of the bias may be due to heat released from the floating bridge's concrete pontoons or heat absorbed from solar radiation that penetrates the surface of the water (Onset HOBO Temp Pro thermistor casings are dark). A possible explanation for the differences in temperatures observed near the bottom may be the presence of cold bottom flow from convection currents generated primarily by the cooling of surface waters in shallow embayments or density currents from the major tributaries (Syck 1964, Gould and Budinger 1958)[5]. The difference in reported bottom temperatures between the Hydrolab and the Onset thermistors may be due to an error in the reported depth (Hydrolab or thermistor chain) or the Hydrolab temperature probe not being allowed to equilibrate to the change in temperature. It

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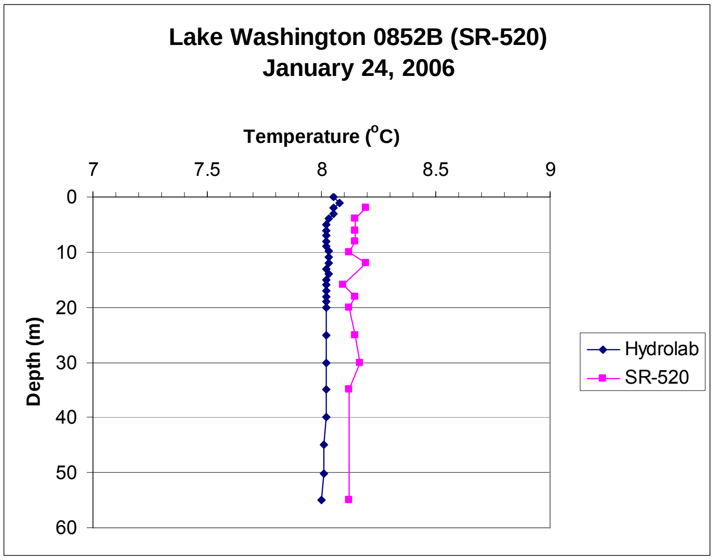
[4] Due to concerns for the safety of the CTD package, the CTD was only used in open water and was not used in the vicinity of the floating bridges, the Lake Union dock or the pier at the Ship Canal locks.

[5] Note that significantly cooler bottom water was detected at all the RBR stations in Lake Washington profiled with the SeaBird CTD (see Figure 18).

might be prudent to check the depth of each Onset thermistor using a pressure transducer on at least an annual basis to verify the accuracy of the stated thermistor depths.

Ideally, both the Hydrolab and Onset thermistors would be checked against a National Institute of Standards and Technology (NIST) certified thermometer accurate to ±0.01 °C on at least an annual basis that might allow for consistent corrections to be made to both instruments that would bring these data into closer agreement. Also, considering the expected magnitude of lake temperature change has been on the order of 0.3 °C per decade, thermistor accuracies much greater than 0.2 °C would improve the likelihood of detecting long-term trends in lake temperature.



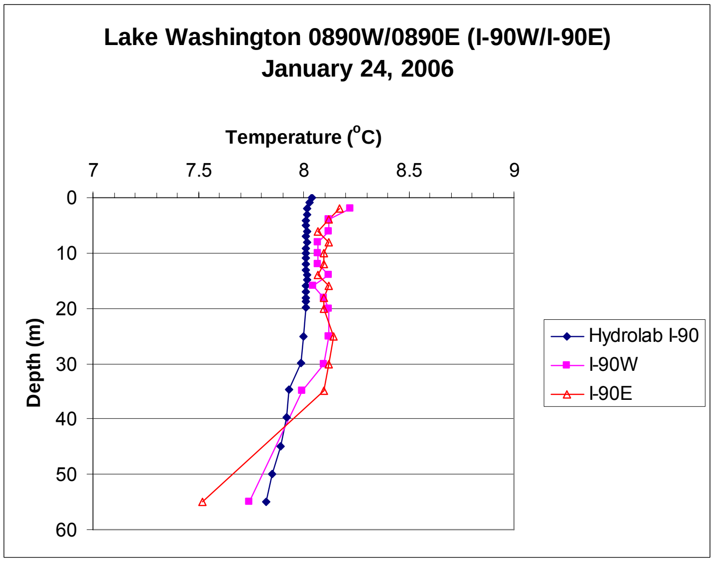
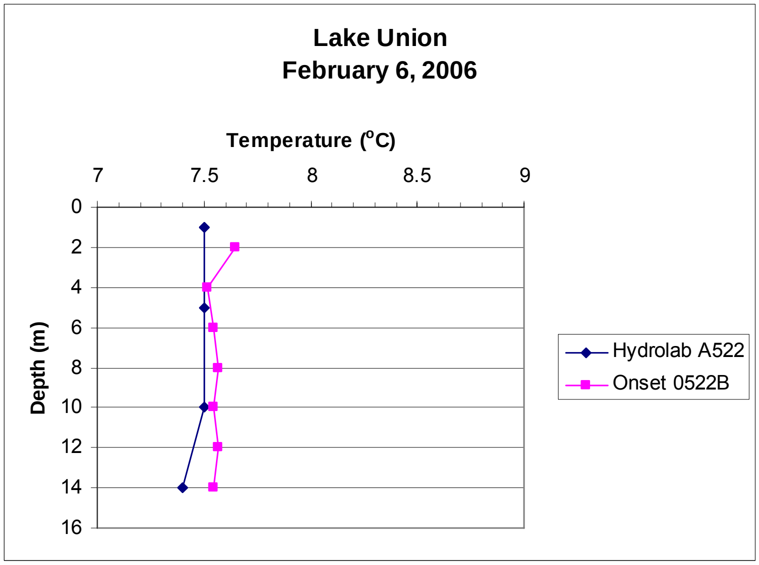


Figure 16. Comparison of Lake Washington Onset profiles with Hydrolab sonde profiles conducted January 24, 2006.

Routine Hydrolab casts from stations 0522B and 0512B on February 6, 2006 in Lake Union and Ship Canal Locks were compared to the Onset thermistor chain profiles recorded at approximately the same time (Figure 17). Comparisons between the two datasets indicate that these thermistors were performing within the specified criterion of ±0.2 °C. Again, the thermistors closest to the surface (2-m depth) appear to have the highest positive bias relative to the Hydrolab data. Ideally, thermistor chains would be deployed some distance away from bridge pontoons to avoid this potential bias.



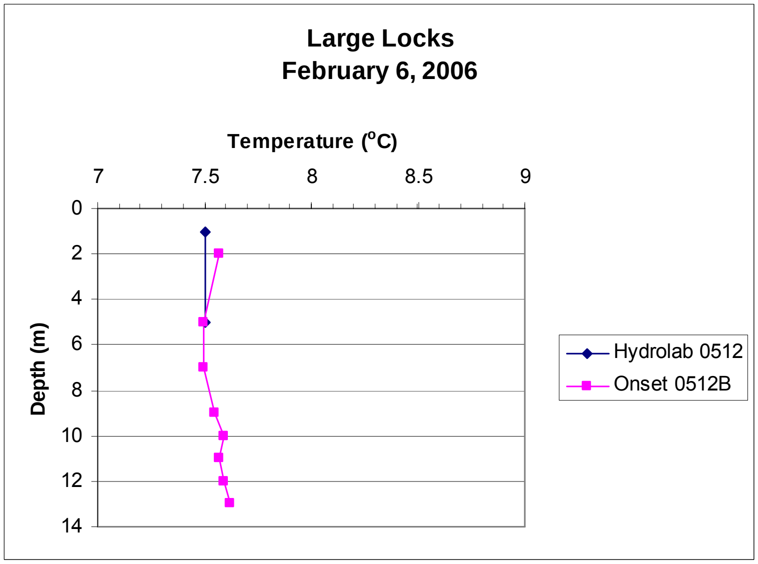


Figure 17. Comparison of Lake Union and Ship Canal locks Onset profiles with Hydrolab sonde profiles conducted February 6, 2006.

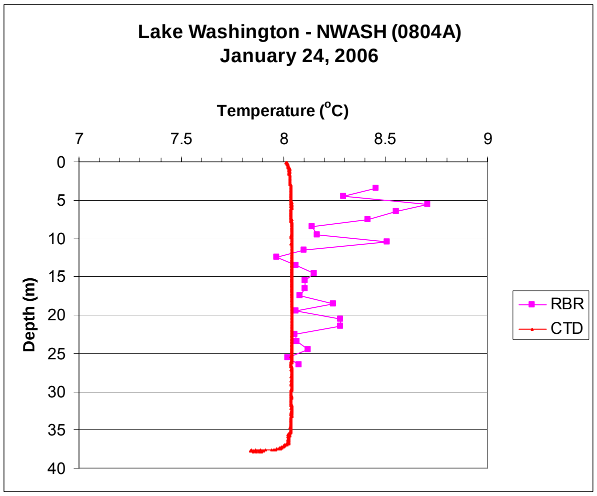
Onset Hobo Water Temp Pro thermistor data have been processed and uploaded to the SQL database (data available from: http://dnr.metrokc.gov/wlr/waterres/hydrology/GaugeSelect.aspx). without qualification. However, a laboratory calibration check is recommended to better compare and cross-calibrate Hydrolab and Onset Hobo Water Temp Pro thermistors. Onset thermistors near bridge pontoons or docks may be biased due to heat stored and released from concrete pontoons or warming of thermistors by solar radiation penetrating the water surface. Ideally, telemetered monitoring buoys would replace the current system, which would eliminate bias due to bridge pontoons and should also minimize the field resources and post-processing effort currently expended downloading and managing the data from each thermistor separately.

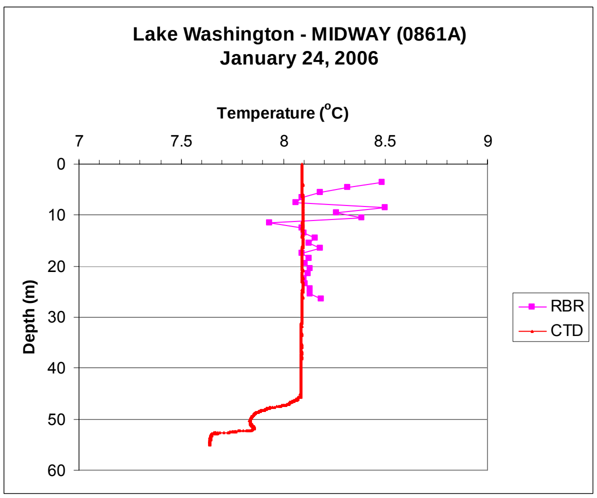
3.2.2 RBR Calibration Check

Sea-Bird CTD casts were conducted at the 3 Lake Washington RBR stations on January 24, 2006: 0804A (NWASH), 0861A (MIDWAY) and 0831A (SWASH). Comparison of CTD and RBR profiles indicated significant calibration errors associated with the RBR thermistor chains (Figure 18). The Sampling and Analysis Plan stated that if recorded profiler temperatures differed by more than 0.2 ^{o}C from the temperature measured by a particular thermistor in the chain, the RBR thermistor chain would be replaced with available equipment from the backup equipment pool and the defective equipment returned for maintenance, calibration, or replacement if under warranty or if funds were available for repair (King County 2005c). Unfortunately, no equipment maintenance funds were available to re-calibrate the chains in 2006 and the number of poorly calibrated thermistors made it nearly impossible to objectively select usable data. Therefore, these data were not loaded into the SQL database and are used in this report only in a qualitative manner. The data may be obtained directly from the author of this report.

Routine Hydrolab casts from stations 0611 and 0612 on February 7, 2006 in Lake Sammamish were compared to the RBR thermistor chain profile at 0641A (LS02A) recorded at approximately the same time (Figure 19). This comparison also indicates significant calibration problems with the RBR thermistors deployed in Lake Sammamish. Therefore, quantitative use of the RBR data was also considered imprudent and these data were not loaded into the SQL database.

Although RBR recommends thermistor chain calibration on an annual basis, annual calibration was not part of the previous research program for which they were purchased (Schock 2002) and resources for annual calibration were unavailable for the initial continuous temperature monitoring program reported on here. If funding was found to perform maintenance and calibration of the thermistor chains, it is still uncertain whether or not the chains would maintain calibration for at least one year. Difficulties with the pressure transducers have also been an ongoing problem that RBR has not resolved. Based on these considerations, the continued use of the RBR thermistor chains is not recommended unless adequate resources become available to properly maintain and calibrate the chains – and a method is developed to monitor calibration performance over time.





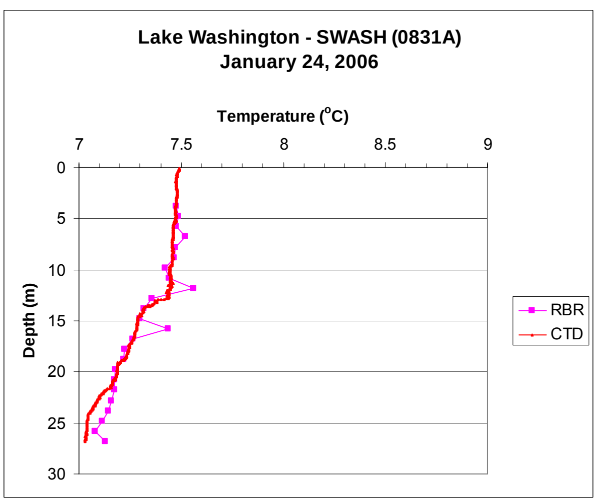


Figure 18. Comparison of Lake Washington RBR profiles with SeaBird CTD profiles conducted January 24, 2006.

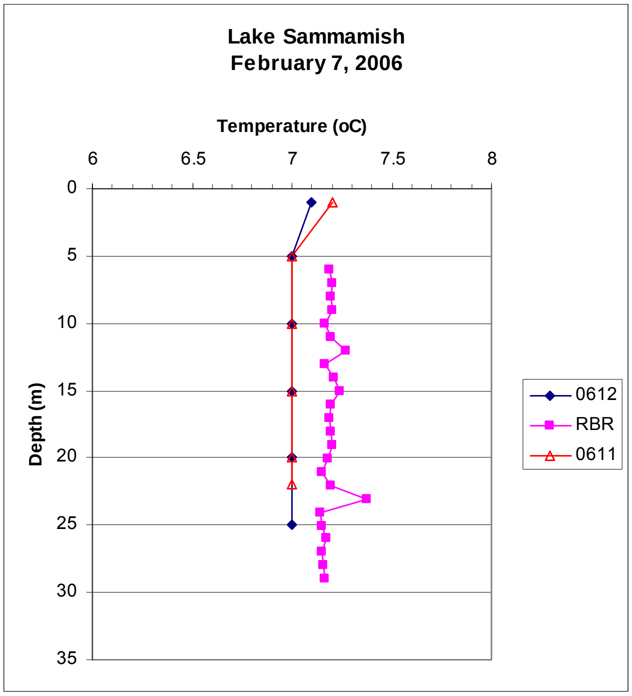


Figure 19. Comparison of Lake Sammamish RBR profile (0641A) with Hydrolab sonde profiles conducted at Major Lakes Monitoring Program stations 0611 and 0612 on February 7, 2006.

3.3 Discussion

The field method chosen to check thermistor calibration was a compromise to avoid retrieving all of the equipment and performing calibration checks in a more rigorously controlled laboratory environment. Although this approach was able to identify the errors in the very poorly performing RBR thermistors, it is not suitable for developing calibration factors that might be used to adjust the thermistor data to more closely correspond to measurements made by more accurate NIST-certified thermometers. A laboratory method to check the calibration of the Onset HOBO Temp Pro thermistors (and Hydrolab thermistors if there is not already a program in place for this) might be a reasonable way to establish the accuracy of the temperature monitoring equipment in use for this study. A laboratory calibration check may also provide adjustment factors that would increase the potential accuracy of the data below the current ±0.2 ^{o}C range currently obtained. Another alternative would be to investigate the purchase of more accurate temperature monitoring equipment. Ideally, the equipment would also allow telemetry of the collected data to minimize expenditure of field resources and provide data and information on system status in real or near-real time. Systems that could be investigated include the Lake Diagnostic System (LDS) (http://www.pme.com/lds.htm) with a temperature accuracy specification of ±0.01 ^{o}C.

4.0. EXAMPLE DATA APPLICATIONS

Three examples are provided below that illustrate the utility of high frequency temperature data collection as compared to routine monthly to bi-monthly mid-day temperature profiling efforts of King County. These examples include: (1) estimates of thermal stress experienced by coldwater fish – particularly Chinook and sockeye salmon migrating through the Ship Canal Locks on their way to their spawning grounds in Sammamish-Washington basin streams and rivers;
(2) calculation of a lake stability index that has been used to evaluate trends in stratification duration and strength in Lake Washington and could be used to evaluate spring and summer phytoplankton bloom dynamics when coupled with frequent measures of phytoplankton biomass; and (3) a qualitative illustration of the basin-scale internal wave dynamics of Lake Washington that have implications for seasonal lake circulation patterns and the spatial and temporal variation of temperature and other water quality constituents throughout the lake.

4.1 Index of Thermal Stress

Previous analyses have suggested a relationship between the number of days the temperature exceeds some threshold and Chinook salmon escapement (including harvest) in the Lake Washington system (Wetherbee and Houck 2001). Elevated water temperatures are also suspected to have caused the apparent loss of approximately half of the 2004 sockeye salmon run between the Ship Canal Locks and sockeye spawning grounds in the Cedar River and other Lake Washington tributaries (Stifler, L., Seattle Post-Intelligencer, July 11, 2005; Cornwall, W., Seattle Times, June 22, 2005).

With a chosen lethal threshold, an Index of Thermal Stress (ITS)[6] can be calculated, which essentially produces degree-day values above a chosen threshold. A threshold of 20 ^{o}C was chosen for use in this report because it is the upper incipient lethal temperature (UILT) for salmon – the water temperature at which approximately half of the population would survive with permanent exposure (Houston 1982). This threshold is also consistent with the observations of Macdonald et al. (2000) that during unusually warm years (mean daily temperatures above 20°C) Fraser River sockeye hormonal and stress indicators suggested that fish were suffering significant physical stress and maturation impairment. Exposure of salmon to temperatures in excess of 20 ^{o}C also appears to be associated with a much higher risk of disease (see summary in Hicks 2002).

As a simple example using 20 ^{o}C as a threshold, a two-day exceedance at 2 ^{o}C [2 day x (22-20) = 4 degree-days] would count as four times as much thermal stress in this index as a one-day exceedance at 21 ^{o}C [1 day x (21-20) = 1 degree-days]. The resulting daily degree-day values can be summarized for the period June 15 through August 15 (the primary sockeye migration period at the Ship Canal Locks). Summary statistics can include the average daily degree-day

[6] The concept of an Index of Thermal Stress (ITS) was developed and applied to an evaluation of temperature management scenarios as part of the Sammamish River Corridor Action Plan (Appendix B, King County 2002b).

value (i.e., the sum of each daily-degree value divided by the number of days between June 15 and August 15 each year, the maximum daily degree-day value each year, and the sum of the daily degree day values each year over the exposure period. These indices of exposure of migrating sockeye to thermal stress could then be compared to various sockeye migration statistics to assess the potential influence of thermal stress on sockeye migration timing and pre-spawn mortality.

One can compare the routine ambient monitoring data from station 0512 at the Ship Canal Locks to the continuous temperature data recorded at 0512B to demonstrate that the continuous temperature data will provide a much more accurate estimate of thermal exposure experienced by salmon migrating through the Ship Canal.

The average surface temperature (0-5 m depth) in the vicinity of the Ship Canal Locks for 2004-2006 based on routine profiling data from Station 0512 and for daily average surface temperatures determined using the thermistor data collected at Station 0512B are shown in Figure 20. In general, surface temperatures do not exceed the 20 ^{o}C temperature threshold at the beginning of the sockeye migration period. Peak temperatures of 22-23 ^{o}C occur in August near the peak migration period. Temperature begins to fall, but are still above the threshold by the end of the sockeye migration through the locks. Although the average temperatures observed on the same days at both stations agree very well, there are many distinct warming and cooling periods between routine profiling dates (see Figure 20) that are captured by the higher frequency observations at 0512B, but are missed by the routine profiles.

The results of the calculation of the ITS by interpolating the observed average surface temperatures between profile dates (Station 0512) and for daily average surface temperatures determined for Station 0512B are presented in Table 4. Overall, there is good agreement between the two data sets for the first and last date that the surface temperature exceeds 20 ^{o}C and the number of days that the threshold was exceeded. However, the average ITS (degree days above 20 ^{o}C), the maximum ITS and the sum of daily ITS values over the summer sockeye migration entry period were different due to the higher resolution of the thermistor data at 0512B that captured brief cooling and warming events over the sockeye exposure period, especially in 2004 (cooling) and 2006 (warming).

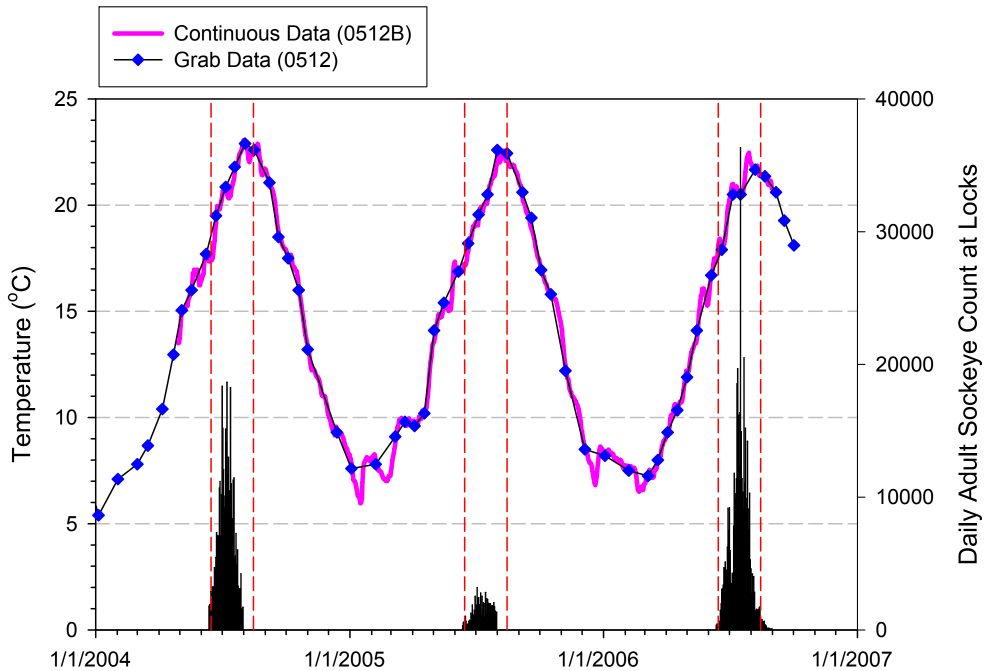


Figure 20. Plot of average surface temperature (0 to 5-m depth) observed at 0512 and 0512B between 2004-2006.

Note: 2006 Data for 0512 and 0512B are incomplete. Red vertical lines indicate the range of dates used to calculate the Index of Thermal Stress. Daily adult sockeye counts at the Ballard Locks (black bars) are also shown. These data were obtained from the Washington Department of Fish and Wildlife website - http://wdfw.wa.gov/fish/sockeye/counts.htm.

Table 4. Summary of Index of Thermal Stress statistics for 2004-2006.

Year	0512			0512B		
	First day of year greater than 20 °C	Last day of year >20 °C	Number of Days >20 °C	First day of year greater than 20 °C	Last day of year >20 °C	Number of Days >20 °C
2004	28-Jun	14-Aug	48	29-Jun	14-Aug	47
2005	11-Jul	13-Aug	34	12-Jul	13-Aug	33
2006	2-Jul	13-Aug	43	29-Jun	13-Aug	46
	Average Degree Days above 20 °C	Maximum Degree Days above 20 °C	Sum degree days > 20 °C	Average Degree Days above 20 °C	Maximum Degree Days above 20 °C	Sum degree days > 20 °C
2004	1.83	2.90	88.1	1.66	3.05	77.9
2005	1.69	2.60	57.4	1.49	2.52	49.2
2006	0.95	1.67	40.9	1.24	2.42	57.2

To evaluate the ITS for potential trends, the cumulative ITS was also calculated for the long term temperature data collected in Lake Washington by the UW for the period 1964 to 2006. These results, along with the results for the routine King County and continuous temperature monitoring location near the locks, are plotted in Figure 21. The long-term data collected in Lake Washington appear to be a reasonable surrogate for thermal stress experienced by salmon migrating through the Ship Canal. This is not surprising since the temperature of the surface of the lake in summer is likely driven almost exclusively by surface heat exchange processes that would be similar across the lake surface – including the Ship Canal. Although there is no statistically significant trend over the period 1964-2006, there is a distinct upward trend beginning in 1980, with the highest ITS estimates occurring in 1998 and 2004 – 2 years that have anecdotally been noted for high incidence of pre-spawn mortality (Chinook in 1998 and sockeye in 2004). The upward trend in thermal stress is consistent with observed warming trends in Lake Washington (Arhonditsis et al. 2004) – daily maximum temperatures were not necessarily higher (mid-summer daily temperatures typically exceed 20 ^{o}C), but periods of elevated temperatures each year appear to be longer and/or more frequent.

The higher total ITS in 2006 based on the continuous thermistor data relative to the estimates based on King County and UW data result because the bi-monthly profiling efforts missed the two brief, but significant, warming periods in July and August (see Figure 20).

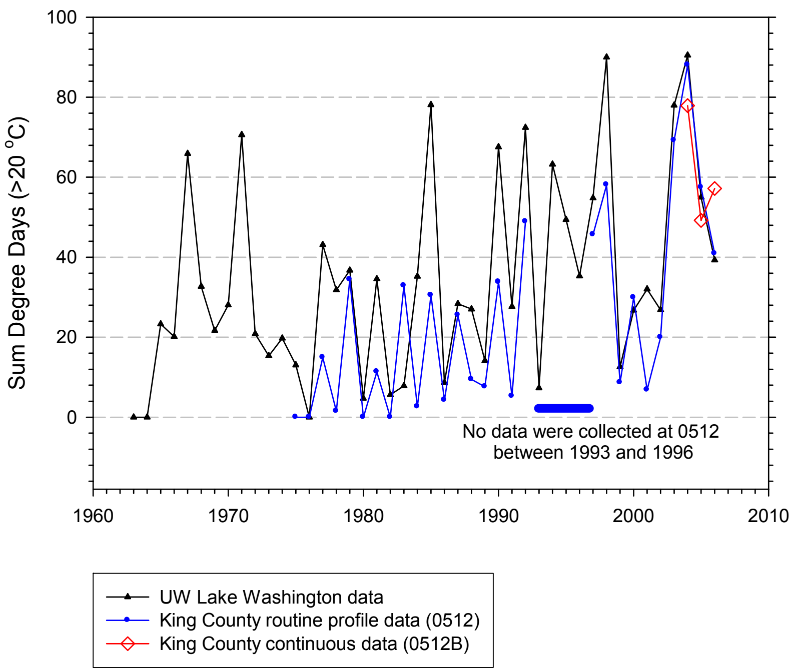


Figure 21. Plot of annual total Index of Thermal Stress based on the University of Washington long-term data set, and stations 0512 and 0512B for the period 1964-2006.

4.2 Lake Washington Thermal Stability

Winder et al. (2004a) identified a statistically significant trend in the onset of spring stratification in Lake Washington using the modified Schmidt stability index as a measure of the strength of lake stratification. Winder et al. (2004a) estimated that spring stratification is ~ 15 days earlier than it was in the 1960s.

The Schmidt Stability Index, as modified by Isdo (1973)[7], is calculated using the following equation:

$$S = A_o^{-1} \sum_{z_0}^{z_m} (z - z_{\overline{p}})(p_z - \overline{p})\, A_z\, \Delta z$$

where,

A_o = Lake surface area (cm^2)
p_z = Density at depth z (g cm^{-3})
$\overline{p}$ = Mean density (g cm^{-3})
z = Depth at measurement point in centimeters
$z_{\overline{p}}$ = Depth in centimeters where mean density is found
A_z = Area at depth z (cm^2)

Winder et al. (2004a) use a daily interpolation of the weekly to biweekly temperature profiling data collected as part of the UW's long-term study to identify shifts in the onset of stratification in the lake. Using the continuous data, it is possible to directly calculate lake stability on a more frequent basis. Here we compare lake stability estimates derived from the UW data and from daily average profile data collected as part of this study at station 0852B – the nearest continuous station to the UW sampling area.

A calendar year scatter plot of the Schmidt Stability Index calculated from the UW data for the period 1964-2006 is shown in Figure 22 to illustrate that the minimum stability occurs in late January or February when the lake is isothermal and coldest and that maximum stability typically occurs in August when peak surface temperatures occur. Also, shown is an operationally defined threshold of 150 gm-cm cm^{-2} used here to identify the onset of stratification and destratification.

[7] Also see Wetzel and Likens (1991), Johnson et al.(1985), and Hutchinson (1975) regarding the calculation and use of the Schmidt stability index.

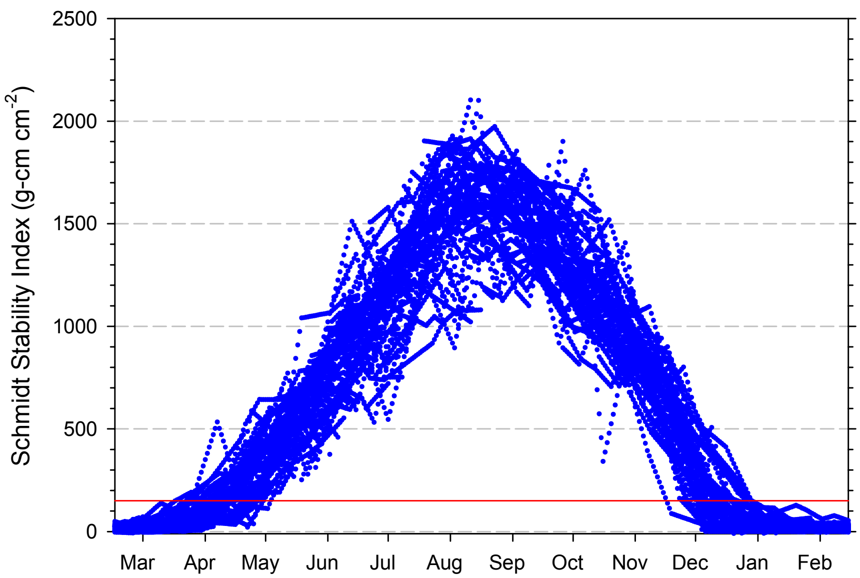


Figure 22. Plot of daily Schmidt Stability Index based on the University of Washington long-term dataset for the period 1964-2006.

Note: Stability threshold of 150 g-cm cm^{-2} is shown as a horizontal red line.

Figure 23 shows the calculated daily long-term stability of Lake Washington for the period 1964-2006 based on the UW data. Figure 24 compares the daily time series of lake stability calculated from UW and King County 0852B data for the period 2005-2006. Overall, there is good agreement in the estimated lake stability between the two datasets, although there is a conspicuous (and yet unexplained) difference between the two data sets on August 23, 2005. However, the stability estimates based on the higher frequency data at 0852B suggest larger fluctuations in lake stability on a daily basis, especially during the onset and duration of summer stratification. The decline in lake stability in late summer appears to be relatively gradual, without the higher frequency variation apparent during the period of increasing stability.

A comparison of the onset and end of stratification[8] and the maximum Schmidt Stability Index calculated using data from 0852B and UW data for 2005 and 2006 are provided in Table 5. The estimates of the onset and end of stratification derived from the two data sets are very similar, but the maximum annual Schmidt Stability Index estimates are different probably due primarily to the spatial and temporal resolution of the two sets of data.

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[8] The thermistors at 0852B were not installed until mid-2005 so no estimate of the onset or duration of stratification can be made for 2005 and the most recent data download was in August 2006 so no estimate can yet be made of the duration of stratification in 2006.

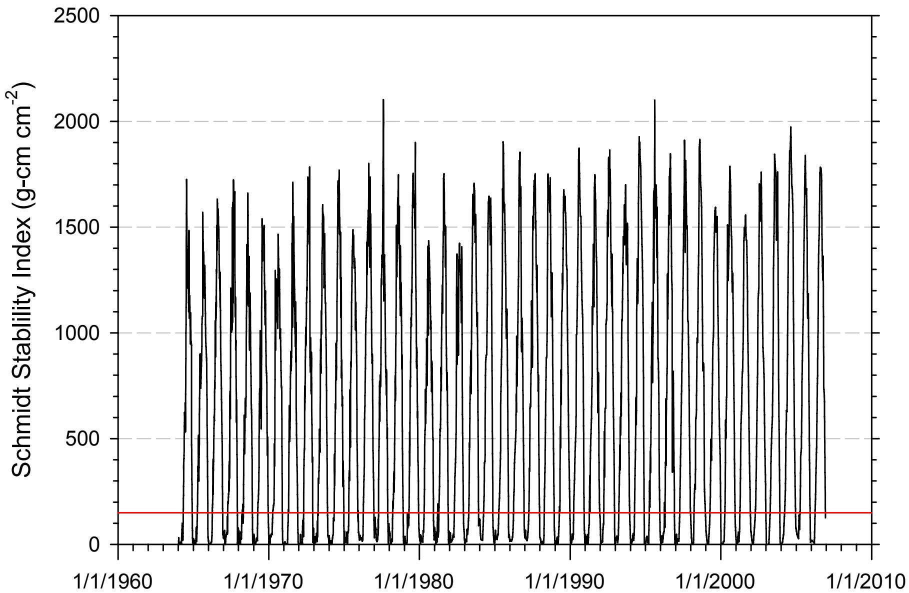


Figure 23. Time series plot of daily Schmidt Stability Index based on the University of Washington long-term dataset for the period 1964-2006.

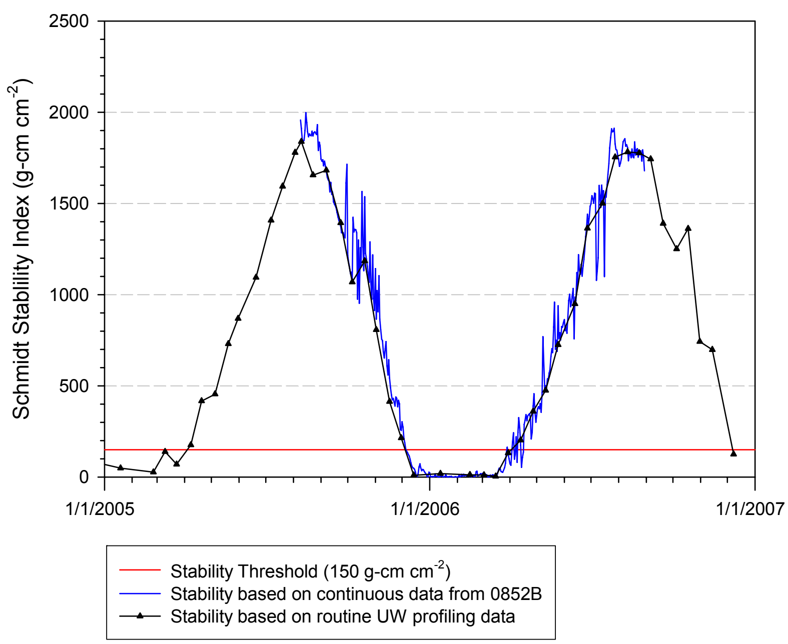


Figure 24. Time series plot of daily Schmidt Stability Index based on the University of Washington and 0852B data for the period 2005-2006.

Note: Stability threshold of 150 g-cm cm^{-2} is shown as a horizontal red line.

Table 5. Summary of estimates of annual stratification onset, end and duration and maximum Schmidt Stability, 2005 and 2006.

	0852B				University of Washington			
Year	Stratification			Schmidt	Stratification			Schmidt
	Onset	End	Duration	Stability[a]	Onset	End	Duration	Stability[a]
2005	na	3-Dec	na	1931.7	3-Apr	2-Dec	243	1839.1
2006	26-Mar	na	na	1912.5	1-Apr	4-Dec	247	1782.7

[a] Units are g-cm cm^{-2}
na - The thermistors at 0852B were not installed until mid-2005 so no estimate of the onset or duration of stratifian can be made for 2005 andd the most recent data download was in August 2006 so no estimate can yet be made of the duration of stratification in 2006.

To illustrate the changes in lake stability that have already been documented (Winder and Schindler 2004a, Winder and Schindler 2004b), the trends in the annual onset, end and duration of stratification and the annual maximum lake stability based on the UW data for the period 1964-2006 are shown in Figure 25. Based on a non-parametric trend test (Mann-Kendall), with the exception of the date the lake becomes destratified, these metrics have statistically significant trends ($p<0.05$). In general, the lake has become more stable earlier in the year and remains stable longer which translates into a longer duration of lake stability. Annual maximum lake stability is also increasing. Some of the ecological effects of these changes have already been explored (e.g., Hampton et al. 2006a, Hampton 2005, Romare et al. 2005, Arhonditsis et al. 2004, Winder and Schindler 2004a, Winder and Schindler 2004b). Other untested possibilities include: (1) potential increases in summer cyanobacteria blooms (Edmondson et al. 2003); (2) progressive oligotrophication of the lake due to a shift from large-celled endemic diatom flora to small cell picoplankton (Fietz et al. 2005); (3) a shift from autotrophic to heterotrophic production (Stockner 1998); or (4) an increase in hypolimnetic oxygen depletion rates (Jankowski et al. 2006).

Unfortunately, it may become impossible to test the first hypotheses (perhaps the hypothesis relevant to the public perception of lake quality) as the resources to continue quantitative phytoplankton analyses by the UW or King County is uncertain at this time. No quantitative phytoplankton analyses have been made on UW samples since some time in 2002, although preserved samples have been archived. King County established a quantitative phytoplankton monitoring program in 2003 (King County 2003b) using capital funds, but the capital project has ended and there is no certainty at this time that resources will be found to continue this effort. Since the UW already has compiled a long-term record of phytoplankton species and biovolume as part of their monitoring program, it would be highly desirable to find resources to continue their effort using the same techniques and level of expertise that they have used in the past (see Edmondson et al. 2003 for a description of their methods). Lacking resources for a university led effort, King County should identify the resources needed to continue the quantitative phytoplankton program established in 2003.

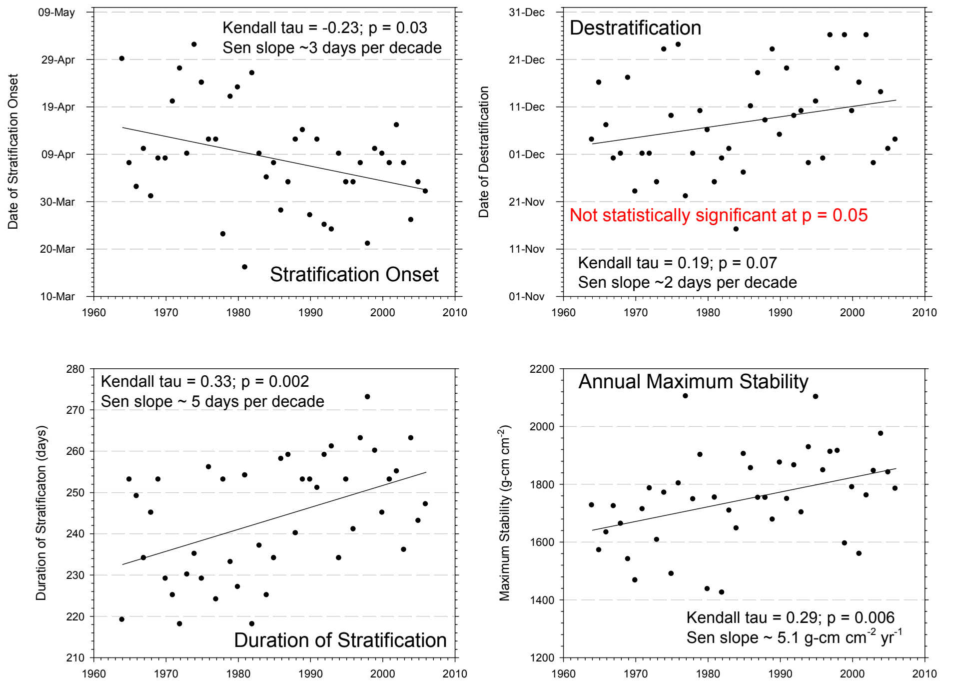


Figure 25. Annual estimates of (A) stratification onset, (B) destratification, (C) duration of stratification, and (D) maximum Schmidt Stability Index based on the University of Washington data for the period 1964-2006.

Note: Stability threshold of 150 g-cm cm^{-2} was used. All trends were evaluated using the non-parametric Mann-Kendall test.

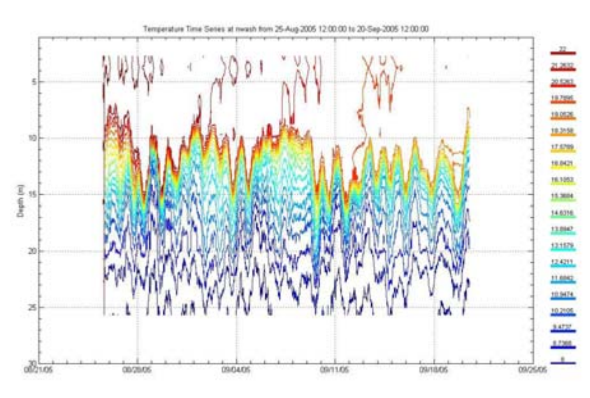
4.3 Lake Washington Basin-scale Internal Waves

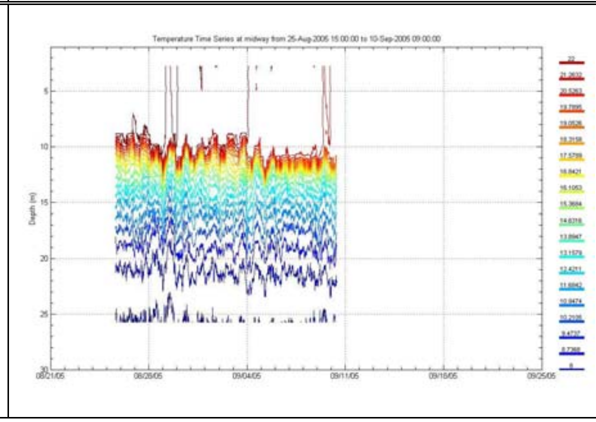
Lakes respond in a variety of rhythmic oscillations to the energy supplied by wind moving over their surface (Wetzel 2001). These oscillations and associated water movements ultimately degrade into turbulent motions. Every lake basin has its characteristic surface and internal oscillation modes that depend on the morphometry of the lake, density stratification and wind periodicity and strength. The importance of understanding these oscillations (also known as seiches) and the turbulence they create in relation to biological productivity has been recognized in recent years (e.g., ASLO 2003, Hodges et al. 2000a, Hodges et al. 2000b).

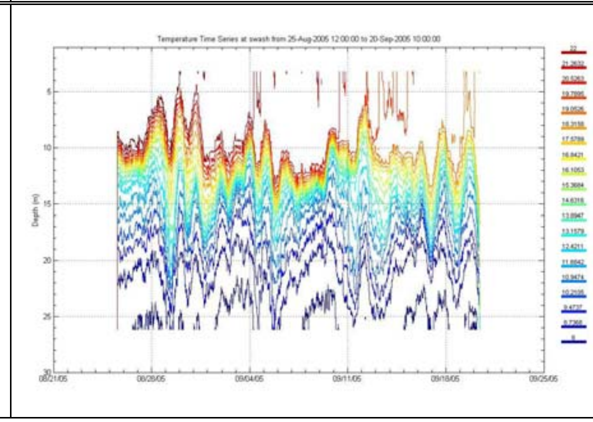
Many lake scientists make an implicit assumption that summer density stratification (and winter stratification in those lakes that cool below 4 ^{o}C or freeze during winter) implies minimal movement of lake strata (Wetzel 2001, p. 93). However, this assumption is quite erroneous. The dynamic internal wave behavior of Lake Washington can be illustrated by comparing the depth-time evolution of temperature recorded by RBR thermistor chains located along the longitudinal axis of the lake from the north (represented by station 0804A / NWASH), near the middle (0861A / MIDWAY), and in the south (represented by 0831A / SWASH) during August 25 to October 20, 2005 (Figure 26).

The sawtooth patterns in the temperature isopleths provide an indication of the amplitude and frequency of internal waves passing each station. The oscillations at the mid-lake station (0861A) are relatively small compared to those at the north or south end during the stratified period (August 25 to September 20 in Figure 26) because these large-scale fluctuations represent extended periods of wind-forced deflection of the thermocline along a north-south gradient due to the predominant southerly winds and the mid-lake station is near the center-point of the axis of this deflection. A conceptual diagram of this situation is presented in Figure 27. This results in upwelling of cooler water in the southern end of the lake and downwelling of warm water in the north end of the lake. As the lake cools during the fall and winds become stronger, these periods of upwelling and downwelling at each end of the lake become longer and more pronounced. A similar situation has been observed in the spring (Schock, K., unpublished data) and the phenomenon has been reported in other large elongated lakes (e.g., Naithani et al. 2003, Hamblin 1978, Stevens and Lawrence 1997). These extended periods of upwelling/downwelling are probably the more likely explanation for observed north-south differences in lake surface temperatures noted in previous studies of Lake Washington (Romare et al. 2005, Arhonditsis et al. 2003), rather than the thermal influence of large tributaries flowing into the north and south ends of the lake.

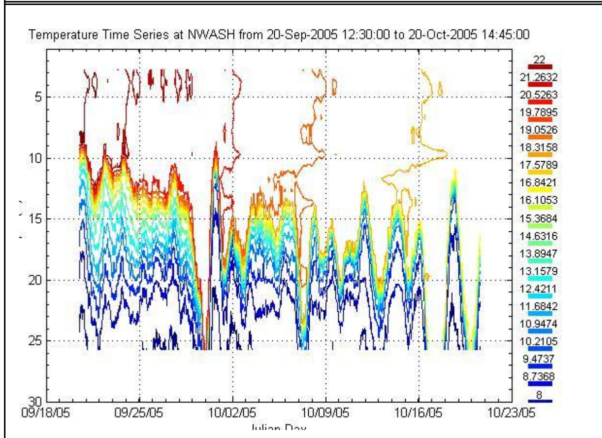
0804A (NWASH)	0861A (MIDWAY)	0831A (SWASH)

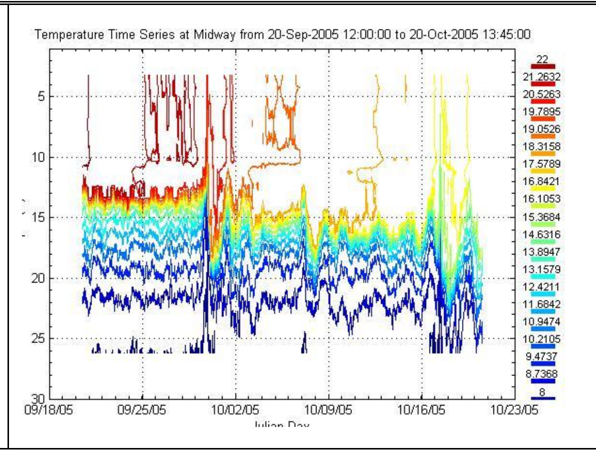


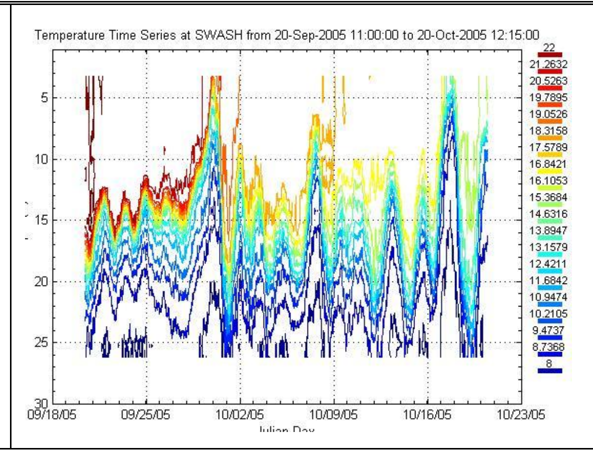




August 25 – September 20, 2005







September 20 – October 20, 2005

Figure 26. Color contour time-depth plots of temperatures recorded by RBR thermistor chains located at 0804A (NWASH), 0861A (MIDWAY) AND 0831A (SWASH) – September 20 – October 20, 2005.

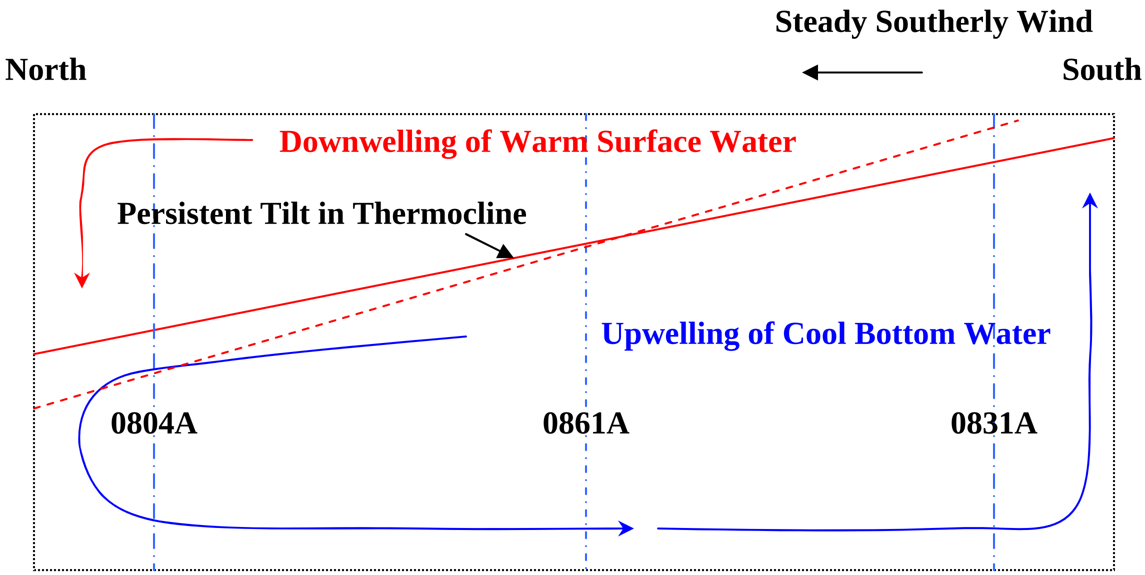


Figure 27. Conceptual diagram of wind-induced deflection of the thermocline.

5.0. CONCLUSIONS AND RECOMMENDATIONS

A number of aquatic ecosystem responses to changing climate have been documented in Lake Washington and other lakes around the world. These responses could only have been detected and understood in the context of changing climate as the result of consistent long-term monitoring of physical, chemical, and biological components of the ecosystem. Further understanding of the effects of changing climate will come from continued comprehensive routine monitoring. However, more frequent sampling (daily to sub-daily) (e.g., Staehr and Sand-Jensen 2007) coupled with modeling (e.g, Peeters et al. 2007) has begun to greatly improve the understanding of linkages between climate and lake ecosystem response. A recent re-assessment of the "Lake Washington Story" (Hampton et al. 2006b), highlighted the key role played by picoplankton and cryptomonads in zooplankton growth that were previously overlooked by other researchers of Lake Washington (also see Hampton 2005, Hampton and Schindler 2005). Considering the hypothesized connection between picoplankton and lake warming trends (Fietz et al. 2005, Stockner 1998), this new twist in the Lake Washington Story deserves further attention.

The initial continuous temperature monitoring effort described in this report, demonstrated the methods and utility of frequent temperature measurement in the three major lakes routinely monitored by King County. These data match less frequent routinely collected data in long-term warming trends but adds more precise information on dates and duration of seasonal stratification and periods of maximum (and minimum) temperatures. These data also inform fish and hydrodynamic studies that historic data cannot. Also, example uses of these data – ITS, thermal stability calculations, and identification of internal seiches have been provided.

Based on the initial continuous temperature study results presented in this report, the following specific recommendations are made:

- Use of RBR thermistor chains should be discontinued.
- Initiate at least annual calibration checks of all temperature monitoring equipment, including profiling sondes used in the routine Major Lakes monitoring program.
- Additional thermistors should be added to Onset thermistor chains to provide temperature records at each location at 1-m intervals from the surface to at least the 30-m depth and perhaps every 2 to 5 meters thereafter.
- Reduce frequency of temperature recording from every 15 minutes to hourly.
- Check the depth of each Onset thermistor using a pressure transducer on at least an annual basis to verify the accuracy of the stated thermistor depths.

- Develop maintenance and performance logs for thermistors to help identify instruments requiring maintenance and instruments that are in working order.

- Ideally, telemetered monitoring buoys would replace the current system, which would eliminate bias due to bridge pontoons and should also minimize the field resources and post-processing effort currently expended downloading and managing the data from each thermistor or thermistor chain.

- Initiate more frequent profiles of phytoplankton biomass, possibly through the use of unattended profilers that include high quality *in situ* fluorometers to better understand the relationship between water column stability and phytoplankton bloom dynamics.

- Continuation of quantitative phytoplankton analysis, especially at the UW that would include the analysis of archived samples using similar techniques and level of training as in their past efforts.

6.0. REFERENCES

American Society of Limnology and Oceanograpy (ASLO). 2003. Report of the Workshop on Emerging Research Questions for Limnology: The Study of Inland Waters. Held December 1-4, 2002, Boulder, CO. Wurtsbaugh, W., J. Cole, D. McKnight, P. Brezonik, S. MacIntyre, and K. Potter (eds.). ASLO, Waco, TX.

Ambrosetti, W. and L. Barbanti. 1999. Deep water warming in lakes: An indicator of climatic change. J. Limnol. 58:1-9.

Arhonditsis, G.B., M.T. Brett, C.L. DeGasperi, and D.E. Schindler. 2004. Effects of climactic variability on the thermal properties of Lake Washington. Limnol. Oceanogr. 49:256-270.

Arhonditsis, G.B., M.T. Brett, and J. Frodge. 2003. Environmental control and limnological impacts of a large recurrent spring bloom in Lake Washington, USA. Environ. Manage. 31:603-618.

Beauchamp, D.A., H.B. Berge, M.M. Mazur, J.K. McIntyre, J.H. Moss, and N.C. Overman. 2004. Trophic dynamics of fishes and zooplankton in Lakes Washington and Sammamish. Final report submitted to King County Water and Land Resources Division, Seattle, WA. Washington Cooperative Fish and Wildlife Research Unit, University of Washington, Seattle, WA.

Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson. 2001. Bull. Amer. Meteor. Soc. 82:399-415.

Coats, R., J. Perez-Losada, G. Schadlow, R. Richards, and C.R. Goldman. 2006. The warming of Lake Tahoe. Climatic Change 76:121-148.

Chorus, I, I.R. Falconer, H.J. Salas, and J. Bartram. 2000. Health risks caused by freshwater cyanobacteria in recreational waters. J. Toxicol. Environ. Health B. Crit. Rev. 4:323-347.

Edmondson, W.T, S.E.B Abella, and J.T. Lehman. 2003. Phytoplankton in Lake Washington: long-term changes 1950-1999. Arch. Hydrobiol. Suppl. 139:275-326.

Eschenbach, W.W. 2004. Climate-change effect on Lake Tanganyika? Nature 15 July 2004, p. 1-2.

Fietz, S. G. Kobanova, L. Izmest'eva and A. Nicklisch. 2005. Regional, vertical and seasonal distribution of phytoplankton and photosynthetic pigments in Lake Baikal. J. Plankton Res. 27:793-810.

Gould, H.R. and R.F. Budinger. 1958. Control of sedimentation and bottom configuration by convection currents, Lake Washington, Washington. J. Mar. Res. 17:183-198.

Hamblin, P.F. 1978. Internal Kelvin waves in a fjord lake. J. Geophysical Research 83:2409-2418.

Hampton, S.E. 2005. Increased niche differentiation between two *Conochilus* species over 33 years of climate change and food web alteration. Limnol. Oceanogr. 50:421-426.

Hampton, S.E. and D.E. Schindler. 2005. Empirical evaluation of observation scale effects in community time series. Oikos 113:424-439.

Hampton, S.E., P. Romare, and D.E. Seiler. 2006a. Environmentally controlled *Daphnia* spring increase with implications for sockeye salmon fry in Lake Washington, USA. J. Plankton Res. 28:399-406.

Hampton, S.E., M.D. Scheurerell, and D.E. Schindler. 2006b. Coalescence in the Lake Washington story: Interaction strengths in a planktonic food web. Limnol. Oceanogr. 51:2042-2051.

Hicks, M. 2002. Evaluating Standards for Protecting Aquatic Life in Washington's Surface Water Quality Standards. Temperature Criteria. Draft Discussion Paper and Literature Summary. Washington State Department of Ecology, Olympia, WA. Publication No. 00-10-070.

Houston, A.H. 1982. Thermal Effects upon Fishes. National Research Council of Canada. Associates Committee on Scientific Criteria for Environmental Quality. Ottawa, Canada.

Hodges, B.R., J. Imberger, B. Laval, and J. Appt. 2000a. Modeling the hydrodynamics of stratified lakes. Hydroinformatics Conference, Iowa Institute of Hydraulic Research, 23-27 July 2000. [http://www.ce.utexas.edu/prof/hodges/documents/hodges_etal_2000_hydroinformatics_abstract.htm accessed Feb. 12, 2007]

Hodges, B.R., J. Imberger, A. Saggio, and K.B. Winters. 2000b. Modeling basin-scale internal waves in a stratified lake. Limnol. Oceanogr. 45:1603-1620. [Hutchinson, G.E. 1975. A Treatise on Limnology. Volume 1, Part 1 – Geography and Physics of Lakes. John Wiley and Sons, New York, NY.

Intergovernmental Panel on Climate Change (IPCC). 2001. Summary for Policy Makers: Climate Change 2001: Impacts, Adaptation and Vulnerability. IPCC, Geneva, Switzerland. [http://www.ipcc.ch/pub/wg2SPMfinal.pdf accessed February 12, 2007]

Isaac, G.W., R.I. Matsuda, and J.R. Welker. 1966. A limnological investigation of water quality conditions in Lake Sammamish. Water Quality Series No. 2. Municipality of Metropolitan Seattle (METRO), Seattle, WA.

Isdo, S.B. 1973. On the concept of lake stability. Limnol. Oceanogr. 18:681-683.

Jankowski, T., D.M. Livingstone, H. Bührer, R. Forster, andP. Niederhauser. 2006. Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: Implications for a warmer world. Limnol. Oceanogr. 51:815-819.

Johnson, N.M., G.E. Likens, and J.S. Eaton. 1985. Chapter IV Mirror Lake – Physical and Chemical Characteristics C. Stability, Circulation and Energy Flux in Mirror Lake. Likens, G.E. (ed.). In: An Ecosystem Approach to Aquatic Ecology. Mirror Lake and its Environment. Springer-Verlag, NY. pp. 108-127.

Karl, T.R. and K.E. Trenbreth. 2003. Modern global climate change. Science 302:1717-1723.

Kerwin, J., 2001. Salmon and Steelhead Habitat Limiting Factors Report for the Cedar – Sammamish Basin (Water Resource Inventory Area 8). Washington Conservation Commission. Olympia, WA

King County. 2002a. Working Draft. Sammamish-Washington Analysis and Modeling Program. Existing Data Review. Prepared by Parametrix and Herrera Environmental Consultants, Inc. King County, Department of Natural Resources and Parks, Water and Land Resources Division, Seattle, WA.

King County. 2002b. Sammamish River Corridor Action Plan. Final Report. Prepared for U.S. Army Corps of Engineers, Seattle District in partnership with King County Department of Natural Resources and Parks, Water and Land Resources Division. Seattle, WA. [http://dnr.metrokc.gov/wlr/waterres/streamsdata/reports/sammrivercorridoractionplan.htm accessed Feb. 12, 2007]

King County. 2003a. Sammamish/Washington Analysis and Modeling Program: Lake Washington Existing Conditions Report. Prepared by Tetra Tech ISG and Parametrix, Inc. King County Department of Natural Resources and Parks, Water and Land Resources Division, Seattle, WA.

King County. 2003b. Sammamish-Washington Analysis and Modeling Program: Major Lakes Phytoplankton Sampling and Analysis Project Plan. Prepared by Curtis DeGasperi. King County Department of Natural Resources and Parks, Wastewater Treatment Division, Seattle, WA.

King County. 2005a. Draft. Sammamish/Washington Analysis and Modeling Program: Lake Sammamish Existing Conditions Report. Prepared by Debra Bouchard, King County Department of Natural Resources and Parks, Water and Land Resources Division, Seattle, WA.

King County. 2005b. Draft Major Lakes Sampling and Analysis Plan. Prepared by Jonathan Frodge, King County Department of Natural Resources and Parks, Water and Land Resources Division, Seattle, WA.

King County. 2005c. Major Lakes Program: Continuous Temperature Sampling and Analysis Plan. Prepared by Curtis DeGasperi, King County Department of Natural Resources and Parks, Water and Land Resources Division, Seattle, WA.

Livingstone, D.M. 2003. Impact of secular climate change on the thermal structure of a large temperate central European lake. Climatic Change 57:205-225.

Macdonald, J.S., I.V. Williams, and J.C. Woodey. 2000. *The effects of in-river conditions on migrating sockeye salmon (Oncorhynchus nerka).* In J.S. Macdonald (ed.) Mortality during the migration of Fraser River sockeye salmon (Oncorhynchus nerka): a study of the effect of ocean and river environmental conditions in 1997. Can. Tech. Rep. Fish. Aguat. Sci. 2315. pp. 39-57.

Mote, P.W. 2003. Twentieth-century fluctuations and trends in temperature, precipitation, and mountain snowpack in the Puget Sound/Georgia Basin region. Canadian Water Resources Journal 28:567-586.

Naithani, J., E. Deleersnijder, and P-D. Plisnier. 2003. Analysis of wind-induced thermocline oscillations of Lake Tanganyika. Environmental Fluid Mechanics 3:23-39.

Newell, J.C. and T.P. Quinn. 2005. Behavioural thermoregulation by maturing adult sockeye salmon (*Onchorhynchus nerka*) in a stratified lake prior to spawning. Can. J. Zool. 83:1232-1239.

O'Reilly, C.M., S.R. Alin, P-D. Pilsnier, A.S. Cohen, and B.A. McKee. 2003. Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. Nature 424:766-768.

Park, S., M.T. Brett, A. Muller-Solger, and C.R. Goldman. 2004. Climatic forcing and primary productivity in a subalpine lake: Interannual variability as a natural experiment. Limnol. Oceanogr. 49:614-619.

Parmesan, C. and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37-42.

Peeters, F., D.M. Livingstone, G-H. Goudsmit, R. Kipfer, and R. Forster. 2002. Modeling 50 years of historical temperature profiles in a large central European lake. Limnol. Oceanogr. 47:186-197.

Peeters, F., D. Straile, A. Lorke and D. Ollinger. 2007. Turbulent mixing and phytoplankton spring bloom development in a deep lake. Limnol. Oceanogr. 52:286-298.

Rattray, M. and S.R. Shetye. 1982. Penetration and dilution of saline water between Lake Union and Lake Washington. School of Oceanography, University of Washington.

Robertson, D.M. and R.A. Ragotzkie. 1990. Changes in the thermal structure of moderate to large sized lakes in response to changes in air temperature. Aquatic Sciences 52(4):360-380.

Romare, P., D.E. Schindler, M.D. Scheuerell, J.M. Scheuerell, A.H. Litt, and J.H. Shepherd. 2005. Variation in spatial and temporal gradients in zooplankton spring development: the effect of climatic factors. Freshwater Biol. 50:1007-1021.

Schock, K. 2002 (rev. 2003). Draft. Sammamish-Washington Assessment and Modeling Program. Hydrodynamic Monitoring Program Sampling and Analysis Plan. Prepared by Kevin Schock, King County Department of Natural Resources and Parks, Wastewater Treatment Division, Seattle, WA

Shindler, D.W., S.E. Bayley, B.R. Parker, K.G. Beaty, D.R. Cruikshank, E.J. Fee, E.U. Schindler, and M.P. Stainton. 1996. The effects of climatic warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. Limnol. Oceanogr. 41:1004-1017.

Schindler, D.W., K.G. Beaty et al. 1990. Effects of climatic warming on lakes of the central boreal forest. Science 250:967-970.

Snover, A.K., P.W. Mote, L. Whitely Binder, A.F. Hamlet, and N.J. Mantua. 2005. Uncertain Future: Climate Change and its Effects on Puget Sound. Prepared by the Climate Impacts Group (CIG), University of Washington, Seattle, WA. Puget Sound Action Team, Office of the Governor, Olympia, WA.

Staehr, P.A. and K. Sand-Jensen. 2007. Temporal dynamics and regulation of metabolism. Limnol. Oceanogr. 52:108-120.

Stevens, C.L. and G.A. Lawrence. 1997. Estimation of wind-forced internal seiches amplitudes in lakes and reservoirs, with data from British Columbia, Canada. Aquat. Sci. 59:115-134.

Stockner, J. 1998. Global warming, picocyanobacteria and fisheries decline: Is there a connection? Picazzo M. (ed.). *Atti del 12^{o} Congresso dell'Associazione Italiana di Oceanologia e Limnologia (Isola Vulcano, 18-21 Settembre 1996).* Volume II – Genova: AIOL. pp. 29-37.

Syck, J.M. 1964. Termal convection in Lake Washington, winter 1962-1963. M.S. thesis, University of Washington, Seattle, WA.

Tomlinson, R.D. R.J. Morrice, E.C.S. Duffield, and R.I. Matsuda. 1977. A baseline study of the water quality, sediments, and biota of Lake Union. Municipality of Metropolitan Seattle, Seattle, WA.

Verberg, P., R.E. Heckey, and H. Kling. 2003. Ecological consequences of a century of warming in Lake Tanganyika. Science 301:505-507.

Vollmer, M.K., H.A. Bootsma, R.E. Heckey, G. Patterson, J.D. Halfman, J.M. Edmond, D.H. Eccles, and R.F. Weiss. 2005. Deep-water warming trends in Lake Malawi, East Africa. Limnol. Oceanogr. 50:727-732.

Walther, G-R., E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebee, J-M. Fromentin, O. Hoegh-Gulberg, and F. Bairlein. 2002. Ecological responses to recent climate change. Nature 416:389-395.

Welch, E.B, D.E. Spyridakis, J.I. Shuster, and R.R. Horner. 1986. Declining lake sediment phosphorus release and oxygen deficit following wastewater diversion. JWPCF 58:92-96.

Wetherbee, P. and D. Houck. 2001. Reconnaissance Analysis of Water Quantity and Quality Trends in the Lake Washington Watershed. Memo and presentation slides (WthrbeeWQWQHouck.pdf).

Wetzel, R.G. 2001. Limnology. Lake and Reservoir Ecosystems. Third Edition. Academic Press, NY.

Wetzel, R.G. and G.E. Likens. 1991. Exercise 3: Physical Characteristics: Lake Models. In: Limnological Analyses. Second Edition. Springer-Verlag, NY. pp. 31-41.

Winder, M and D.E. Shindler. 2004a. Climate change uncouples trophic interactions in an aquatic ecosystem. Ecology 85:2100-2106

Winder, M. and D.E. Schindler. 2004b. Climatic effects on the phenology of lake processes. Global Change Biology 10:1844-1856.