Estimating the Thermal Effects of a Hypothetical Hypolimnetic Withdrawal from Lake Sammamish

October 2018

A service provider to the
King County Flood Control District.

Estimating the Thermal Effects of a Hypothetical Hypolimnetic Withdrawal from Lake Sammamish

Prepared for:

King County Flood Control District

Submitted by:

Curtis DeGasperi and James Bower
King County Water and Land Resources Division
Department of Natural Resources and Parks

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

Acknowledgements

The authors would like to thank Scott Stolnack (Science and Technical Support Section) for technical editing support. The authors would also like to acknowledge Kate Akyuz (Willowmoor Project Manager, River and Floodplain Management Section), Thomas Bannister (River and Floodplain Management Section) and staff of the Science and Technical Support Section (Debra Bouchard, Kate O'Laughlin, Jim Simmonds, and Dave White) for their thoughtful reviews of this report.

Citation

King County. 2018. Estimating the Thermal Effects of a Hypothetical Hypolimnetic Withdrawal from Lake Sammamish. Prepared by Curtis DeGasperi and James Bower, Water and Land Resources Division. Seattle, Washington.

Table of Contents

Figures

Appendices

EXECUTIVE SUMMARY

As part of the Willowmoor Floodplain Restoration Project, the King County Flood Control District is investigating options to reduce temperatures in the upper Sammamish River downstream of the outlet of Lake Sammamish in partnership with the Washington Recreation and Conservation Office, Salmon Recovery Funding Board. Reducing water temperatures could benefit adult Chinook that migrate up the river to spawning areas in Bear Creek and that pass through Lake Sammamish to spawning areas in Issaquah Creek. The 1999 listing of Puget Sound Chinook salmon under the federal Endangered Species Act (ESA) triggered an intensive effort to identify causes of population declines and measures to restore or enhance suitable habitats. Lake Washington-Sammamish River Chinook are identified as one of twenty-two Puget Sound conservation populations under ESA management.

In addition to ESA-listed Chinook, Lake Sammamish is home to the last remaining run of kokanee, a type of land-locked sockeye salmon, within the Lake Washington-Sammamish system. Historically, native kokanee were abundant in Lake Washington and Lake Sammamish, but by the 1980s, there were only three runs of kokanee, two of which resided in Lake Sammamish before spawning in tributary creeks. Two of these runs have since become extinct. The last remaining Lake Sammamish run appears to be in decline. One of the limiting factors for kokanee survival appears to be the amount of cold, well-oxygenated lake habitat during summer.

One of the temperature reduction options being considered as part of the Willowmoor project is late summer pumping of cold water from 15 m below the surface of Lake Sammamish and release of that water at the upstream end of the Sammamish River (the "Hypolimnetic Withdrawal Option"). This report describes the results of analyses conducted to determine the potential effect of that option on the amount of Lake Sammamish kokanee habitat present during the most stressful summer months. Using historical Lake Sammamish temperature data collected over an eight-year period (1995–2002) to describe the range of kokanee habitat volume, we estimated the change in that habitat under two cold water withdrawal scenarios (pumping of 10 and 20 cubic feet per second [cfs] during late summer).

Based on the study results, withdrawal of up to 20 cfs of water from the 15 m depth in Lake Sammamish between mid-July to mid-September would have relatively little effect on thermocline depth, thermal stability, or the depth of the 17°C isotherm. The small effect on lake thermal structure is likely due to selective withdrawal of a small amount of cold water relative to the total volume of water below 15 m. The annual withdrawal of 20 cfs from July 15 to September 15 is conservatively estimated as no more than about 3 percent of the total volume of the lake below 15 m.

Based on the evaluation of historical lake temperature and dissolved oxygen data, September is the month with the least amount of kokanee habitat. In some years, even with no withdrawal of cold water, there is little or no optimal kokanee habitat in Lake

Sammamish. Optimal habitat was defined as water with temperatures below 17°C and dissolved oxygen greater than 8 mg/L. In the best years, this optimal habitat is still limited to no more than 15 percent of the total volume of the lake in September. Conversely, the uninhabitable portion of the lake in September for kokanee (defined as water with temperatures greater than 17°C or dissolved oxygen less than 4 mg/L) is typically greatest in September. Between 1995 and 2017, the proportion of the lake considered to be uninhabitable for kokanee in September ranged from 68 to 97 percent.

Consistent with the estimated effect of the hypothetical withdrawals on lake thermal structure, the estimated effects on lake kokanee habitat volume were also small compared to the total volume of the lake. However, because the amount of kokanee habitat, particularly in September, is small relative to the total volume of the lake, the effect of the withdrawal on kokanee habitat is potentially more detrimental. The long-term average amount of optimal kokanee habitat in September is predicted to decline 10 to 20 percent under the withdrawal scenarios modeled. Under extreme single-year conditions, the baseline (no withdrawal) scenario had zero optimal kokanee habitat, and sub-optimal habitat (the best remaining habitat) declined by 33 percent for the 10 cfs scenario and 59 percent for the 20 cfs scenario.

Considering these existing conditions, the anticipated average reductions in "optimal" (10 to 20 percent) and other marginal ("sub-optimal," and "high risk") habitats under the withdrawal scenarios could have direct, indirect, and cumulative adverse impacts to the native Lake Sammamish kokanee population.

1.0. INTRODUCTION

As part of the Willowmoor Floodplain Restoration Project, the King County River and Floodplain Management Section was tasked with seeking external funding to investigate options to reduce water temperatures in the upper Sammamish River downstream of the outlet of Lake Sammamish (FCDECM 2016-04.1). The Salmon Recovery Funding Board has awarded the project $400,000 to date to study cold water supplementation alternatives for the project.

Temperatures in the Sammamish River during the summer routinely exceed aquatic life temperature criteria for salmon-bearing streams. The 1999 listing of Puget Sound Chinook salmon under the federal Endangered Species Act (ESA) triggered an intensive effort to identify causes of population declines and develop measures to recover populations. Lake Washington-Sammamish River Chinook are one of twenty-two Puget Sound conservation populations under ESA management,[1] and reducing water temperature during the adult upstream migration period was identified as a potentially important action to support Chinook recovery in the watershed.

In addition to ESA-listed Chinook salmon, Lake Sammamish is home to the last remaining run of kokanee, a type of land-locked sockeye salmon, within the Lake Washington-Lake Sammamish system. Kokanee are not listed under the ESA, but the run is considered to be in grave danger of extinction, and is the current focus of multi-agency recovery efforts.

One of the temperature management options under consideration as part of the Willowmoor project is late summer pumping of cold water from Lake Sammamish and release of that water at the upstream end of the Sammamish River. This report describes the results of analyses conducted to determine the potential effect of cold lake water withdrawal on kokanee habitat in Lake Sammamish during the critical summer rearing period.

1.1 Objectives

The overall objective of the work described in this report was to evaluate the effect of cold lake water withdrawal on the quantity of kokanee habitat in Lake Sammamish. This objective was accomplished by compiling available long term lake temperature monitoring data and using the data to model the extraction of cold water from the lake during the period from July 15 to September 15. Two potential withdrawal scenarios were analyzed: withdrawals of 10 and 20 cubic feet per second (cfs).

Specific tasks to meet these objectives were:

[1] The Sammamish River population includes spawning populations in Kelsey, North, Little Bear, Bear/Cottage Lake and Issaquah creeks. Of those creeks, Bear/Cottage Lake and Issaquah creeks are considered Tier 1, or highest priority areas for conservation and restoration.

- Develop temperature and dissolved oxygen thresholds that could be used to define the amount and quality of lake kokanee habitat.
- Compile and analyze long term lake monitoring data for temperature and dissolved oxygen (DO) to illustrate historical trends in lake kokanee habitat.
- Revise temperature model input files as needed to create the two withdrawal scenarios (10 and 20 cfs).
- Run the temperature model with the two new sets of input files.
- Estimate the volume of available habitat for kokanee salmon for each model run and the baseline condition over an 8 year period representing a range of lake temperature and DO conditions.[2]
- Compare the volume of kokanee habitat under the two management scenarios to each other and to the baseline condition.
- Summarize the results in tables and graphs, and synthesize the information to evaluate the potential effects of the hypothetical withdrawals on lake thermal structure and kokanee habitat volume.

[2] A calibrated water quality model of lake dissolved oxygen concentrations is not available at this time. In this analysis, historical dissolved oxygen data are used in conjunction with the modeled temperature data to evaluate the effects of the proposed withdrawals on kokanee habitat.

2.0. BACKGROUND

The Sammamish River is a low-gradient, 13.5-mile-long river that connects Lake Sammamish to Lake Washington. Significant tributaries to the river include Bear Creek, Little Bear Creek, North Creek, and Swamp Creek. Lake Washington drains to Puget Sound via the Ship Canal connecting Lake Washington to Lake Union and the Hiram M. Chittenden Locks (Locks). The Ship Canal and Locks, constructed by the U.S. Army Corps of Engineers (USACE) in the early 1900s, resulted in the lowering of Lake Washington by about 9 feet in 1916 (Chrzastowski, 1983).

In the 1960s, the USACE dredged and widened the Sammamish River, straightened and modified the channel between Lake Sammamish and Bear Creek, and constructed a weir at the outlet of Lake Sammamish.[3] The purpose of the project was to reduce flooding of the agricultural lands in the river valley. As the local sponsor for this project, King County assumed responsibility for maintaining the constructed channel. Since the 1960s, a number of plans and projects have been proposed to improve the habitat quality of the river, in particular, projects aimed at improvements in the Transition Zone (TZ) between the outlet weir and Bear Creek (e.g., NHC, 1992; King County and USACE, 2002; Chin et al., 2003).

In 2013, the King County Flood Control District initiated the Willowmoor Floodplain Restoration Project. The project seeks to address a number of flood control issues related to the Sammamish River TZ. The TZ is 1,432 feet long with a 12-foot-wide low-flow channel and a 200-foot-wide high-flow channel (Chin et al., 2003). A concrete weir, located at the upstream end of the TZ, is designed to control low to moderate water levels in Lake Sammamish. The TZ downstream of the weir has a relatively steep gradient of 0.47 percent, dropping 6.75 feet in 1,432 feet and controls high water levels in Lake Sammamish. The remainder of the Sammamish River has a bed slope of 0.019 percent, falling 12.7 feet in over 13 miles (Chin et al., 2003).

Over time, increased density of the vegetation in the TZ, paired with increasing backwater effects from the urbanizing Bear Creek watershed, have decreased the TZ's effectiveness at providing lake level control for extreme high flow events. By agreement with Lake Sammamish property owners, King County crews now annually trim the low-flow channel willow buffer and mow the grass in the high-flow channel to maintain the TZ's conveyance capacity. This ongoing maintenance, however, degrades habitat for fish and results in the need for frequent and costly mitigation. Threats to salmon are potentially compounded by the relatively warmer water entering the river from the surface of Lake Sammamish, albeit a natural phenomenon of low elevation lake outlets, and in the slow-moving and poorly shaded Sammamish River.

The goals of the Willowmoor Floodplain Restoration Project are to reconfigure the TZ to:

[3] The Sammamish River had already been substantially straightened and the original valley wetlands drained for agricultural use following the development of the Ship Canal and Hiram M. Chittenden Locks early in the 20th century (Collins, 2001; King County, 2008).

1. Ensure the TZ continues to provide necessary lake level control, flow conveyance, and downstream flood control while also reducing the frequency and duration of high winter and spring lake levels.
2. Enhance habitat conditions in the river, tributaries, and adjacent wetlands for Chinook salmon and other fish and wildlife species.
3. Reduce the costs of maintaining the TZ.

Eight cold water supplementation strategies were evaluated as part of the Willowmoor conceptual design process that concluded in 2016. Three alternatives were moved forward for consideration for the preliminary design phase, currently underway:

- Concept 1 – Hypolimnetic Withdrawal from Lake Sammamish. Withdrawal of up to 20 cfs from the hypolimnion of Lake Sammamish to replace the equivalent amount of flow into the river at the weir.
- Concept 2 – Pumped Groundwater. Withdrawal of up to 3 cfs of deep ground water that is discharged into the side channel or pools in the river.
- Concept 7 – Riffle-Pool and Hyporheic Transition Zone. The original concept included excavation of the entire transition zone, which was not deemed cost-effective. This alternative will be moved forward at a smaller scale, i.e. intermittent pools that are over-excavated and filled with gravel to provide local cool spots with hyporheic connection.

A fourth alternative is also under consideration. This alternative is a heat exchange system that would route warm lake surface water along the bottom of Lake Sammamish where the water is coldest and release the cooled water at the Sammamish weir (Concept 8). It was originally not advanced because it had an effect similar to, but more expensive than the hypolimnetic withdrawal option, but may be reconsidered in light of the results of this study.

The subject of the analyses presented in this report is Concept 1, the hypolimnetic withdrawal alternative.

2.1 Sammamish Chinook Salmon

The 1999 listing of Puget Sound Chinook under the federal ESA triggered an intensive effort to identify causes of population declines and measures that could be taken to improve existing conditions. Lake Washington-Sammamish River (Sammamish) Chinook are one of twenty-two Puget Sound conservation populations identified by the NOAA National Marine Fisheries Service. Sammamish Chinook spawn in Kelsey, North, Little Bear, and Bear-Cottage Lake creeks, and in Issaquah Creek, with most naturally spawning Chinook returning to the Bear-Cottage Lake Creek system (since 1999, approximately 72 percent of naturally spawning Sammamish Chinook returned to Bear-Cottage Lake Creek). The majority of Chinook spawning naturally in the Sammamish system are strays from the

Issaquah hatchery (WDFW data). The overwhelming majority of Chinook in the Sammamish system are Chinook returning to the hatchery (approximately 92 percent 1999–2017).

The Sammamish stock is derived from Green River Hatchery Chinook used in the Issaquah Salmon Hatchery (approximately river mile 3.5 on Issaquah Creek) since its construction in 1936, and planted elsewhere in the Lake Washington system during the middle 20th Century (Ajwani, 1956). Current hatchery operations require at least 680 adult females to produce a 2019 goal of 3 million eggs (Darin Combs, WDFW, pers. comm., email, October 25, 2018). The hatchery has a long-term goal that at least 50 percent of the returning adults be of natural origin (i.e., non-hatchery). However, the current proportion of natural-origin Chinook returning to the hatchery is much smaller (average 6.2 percent, 2012–2017).

Surplus Chinook captured at the Issaquah hatchery weir not needed for hatchery operations are released into the upper reaches of Issaquah Creek. The removal of a partial migration blockage upstream of the hatchery in 2013 opened at least 5 miles of habitat for colonization. The available data for the numbers of returning adult naturally spawning Chinook to the Sammamish system are provided in Figure 1.

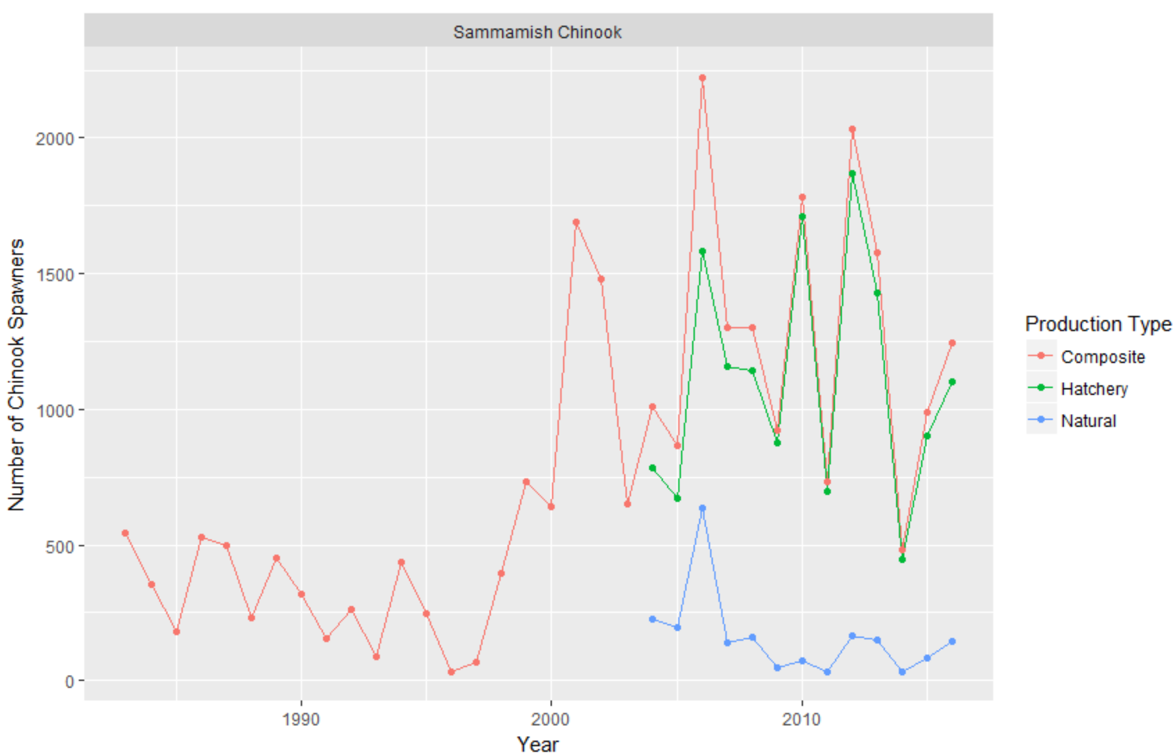

Figure 1. History of annual adult Chinook escapement for the Sammamish River system. Data downloaded from the Washington Department of Fish and Wildlife.[4]

[4] Washington Department of Fish and Wildlife: https://data.wa.gov/Natural-Resources-Environment/WDFW-Salmonid-Stock-Inventory-Population-Escapemen/fgyz-n3uk/data

Beginning in 1997, the USACE undertook a series of studies of Chinook, sockeye, and coho salmon and steelhead trout in the western Lake Washington watershed (SPU and USACOE, 2008). As part of that effort, a river temperature study was conducted in 1998 in conjunction with an adult Chinook tracking study (Martz et al., 1999). During the 1998 study, tagged fish entered the Sammamish River between August 30 and October 29 and fish were detected at Marymoor Park from August 31 to October 29 (Fresh, 1999).[5] Fresh (1999) also noted dead Chinook above and below the locks as well as in the Sammamish River above and below the confluence with Bear Creek. Recent thermal tagging studies by the Muckleshoot Indian Tribe Fisheries Division in 2010, 2011, 2012 and 2016 detected Chinook entering the river as early as August 1, though the average entry to the river was September 8 (Eric Warner, Muckleshoot Indian Tribe Fisheries Division, pers. comm., email, September 25, 2018). In 2015, Chinook migration through the Sammamish River peaked around September 18, though small numbers of Chinook were still encountered when surveys ended on October 30 (R2 Resource Consultants, 2015).

It has also been observed that adult Chinook that arrive earlier in the summer tend to hold just above the locks for longer periods than fish that arrive later (Fresh et al., 1999; SPU and USACOE, 2008). These fish tend to be found at depth in the vicinity of the saltwater drain, which may provide somewhat cooler thermal habitat. On average, adult Chinook spend 1 day in the Ship Canal and 2 to 5 days in Lake Washington before beginning to migrate through the Sammamish River (Fresh et al., 1999; SPU and USACOE, 2008). Chinook also typically spent a number of days in the Sammamish River before entering their spawning tributaries. Of the 29 tagged fish that entered the Sammamish River in 1998, the fastest fish spent 4.32 days in the river while the slowest fish was in the river 15.38 days (Fresh et al, 1999). Fish that were tagged at the Locks before August 23 spent longer periods in the river than fish tagged after this date. Female fish also took longer than males to travel through the river. Much of the time in the river was apparently spent holding in pools. One tagged fish spent 9 days in one pool, while another fish spent 24 days in a single pool. More recent studies indicate that the average transit time through the Sammamish River to Lake Sammamish was 15 days (E. Warner, pers. comm.).

While adult sockeye appear to find cold water in a narrow temperature range in Lake Washington, adult Chinook do not appear to have such a preference and experience a variety of temperatures while in the lake (SPU and USACOE, 2008). Tagging studies showed that temperatures occupied by fish in the lake ranged from 9 to 21 degrees Celsius (°C). Adult Chinook also did not appear to favor the most apparent cold water refuges at large tributaries along the Sammamish River, but rather favored shallow pools (Fresh et al., 1999). The pool most favored by adult Chinook in 1998 was upstream of the confluence with Bear Creek where the river was warmest. However, Fresh et al. (1999) reported that these pools contained water at the bottom that was cooler than the surface water by as much as 2°C.

[5] Fish were tagged at the Locks beginning in August, although Chinook had been present as early as June and the number of Chinook at the locks peaked in late July, which more typically occurs in late August (Fresh et al., 1999).

Fresh (1999) hypothesized that the dead Chinook encountered in the Sammamish River in 1998 may have been killed by high water temperatures in the river (e.g., >22°C on September 8, 1998) or they could have been killed by the cumulative effects of high temperatures in the Ship Canal and the Sammamish River. It has also been suggested that the apparently higher pre-spawn mortality rate of Chinook observed in Bear and Issaquah creeks relative to pre-spawn mortality in the Cedar River observed between 2002 and 2005 may have been due in part to the relatively high temperatures experienced by fish migrating through the Sammamish River (Berge et al. 2006). Fresh (1999) suggested that warm water in the Sammamish River might represent a significant impediment to passage of adult Chinook and he recommended the construction of pools that might serve as cool water refuges. The potential influence of water temperature on adult Chinook behavior was also suggested by the fact that fish were detected at the upstream tag monitoring station for periods often less than a minute and that over 70 percent of the fish were detected at night at this location (Fresh, 1999).

Additional hypotheses may also fit these observations. For example, the rapid nighttime passage over the shallow weir might also be attributed to predator avoidance. The long holding times at the Locks and in the Sammamish River may be more related to waiting for migration cues such as increases in flows that coincide with cooler weather or physiological cues such as the level of gonadal maturity and body energy content (Strange, 2007). Strange (2007) notes that multiple years of consistent tracking and thermal tagging data are needed to evaluate competing hypothesis regarding adult salmon migration behaviors. For example, Strange's (2007) studies on Klamath River Chinook have shown that:

"[U]npublished results from the 2002 study year indicated that adult Chinook migration in the KRB [Klamath River Basin] was inhibited when mean daily water temperatures ≥22°C, at which point adult Chinook would seek out and reside in thermal refuges or delay migration and continue to hold in the estuary/nearshore. Since 2002 this relationship has been determined to be dependent on whether river temperatures were rising or falling. Tagged Chinook were observed migrating and ignoring thermal refuges at mean daily water temperatures up to 23.6°C during periods of falling temperatures, and observed ceasing migration and retreating to thermal refuges at mean daily water temperatures of only 20.9°C when water temperatures had started rising. In 2005 this relationship held true with the initiation of migration occurring when mean daily water temperatures where as high as 23.5°C (e.g. 8/11/05). Thermally induced cessation of migration occurred at mean daily water temperatures as low as 22.3°C (e.g. 8/21/05), although temperature dynamics during 2005 did not create a situation where mean daily water temperatures dropped below 21°C followed by a subsequent rise. Thus in the absence of evidence to the contrary, it can be concluded that the thermal threshold for migration inhibition for KRB adult Chinook salmon occurs at mean daily water temperatures above 23.5°C if temperatures are falling, at mean daily water temperatures below 21.0°C if temperatures are rising, and at mean daily water temperatures above 22.0°C if temperatures are stable."

Water temperature is not the only presumed limiting factor for Sammamish Chinook, although thermal stress may be a compounding factor for mortality due to parasites,

pathogens and/or contaminant exposure (Cardno, 2017). Indications of *Flavobacterium columnare* (i.e., Columnaris) were observed in 31 percent of the pre-spawn mortality Chinook identified in a 2016 pre-spawn mortality study of the Sammamish River (Cardno, 2017). However, the observed extent of the infections did not suggest that Columnaris was the primary cause of death. Cardno (2017) also suggested that Sammamish River salmon may be adversely affected by various contaminants, particularly during late summer storm events. The connection between contaminated stormwater runoff and coho pre-spawn mortality has been well documented for this region (Feist et al., 2018).[6] A similar causal connection between stormwater and Chinook pre-spawn mortality has not been made.

2.2 Lake Sammamish Kokanee

Unlike their larger relative the sockeye salmon, kokanee do not migrate to the ocean but spend their entire lives in fresh water. Lake Sammamish kokanee migrate from streams as inch-long fry and spend two to four years in Lake Sammamish before returning to natal streams to spawn in the late fall and early winter.

Kokanee historically existed in the smaller tributaries to Lake Washington and the Sammamish River, and the Lake Sammamish watershed. Today they are typically found only in Lake Sammamish and its tributary streams. The Lake Sammamish kokanee population once regularly numbered in the thousands of fish, but the adult population has dipped below 200 seven times since 1996 (see Figure 2). Periods of low kokanee spawner abundance may be a result of normal population cycles; however, recent trend analyses indicate that long-term spawner abundance is downward. Figure 3 illustrates the moving 10-year geometric mean spawner abundance. A petition was filed to list Lake Sammamish kokanee under the ESA in July 2007. The U.S. Fish and Wildlife Service determined that listing was not warranted in October 2011. Regardless, the Lake Sammamish Kokanee Work Group was formed by local, state and federal agencies and others to prevent the extinction of Lake Sammamish kokanee.[7]

[6] Studies have shown that chum salmon are unaffected by the same stormwater runoff that causes coho pre-spawn mortality (McIntyre et al., 2018).
[7] Lake Sammamish kokanee: https://www.kingcounty.gov/services/environment/animals-and-plants/salmon-and-trout/kokanee.aspx

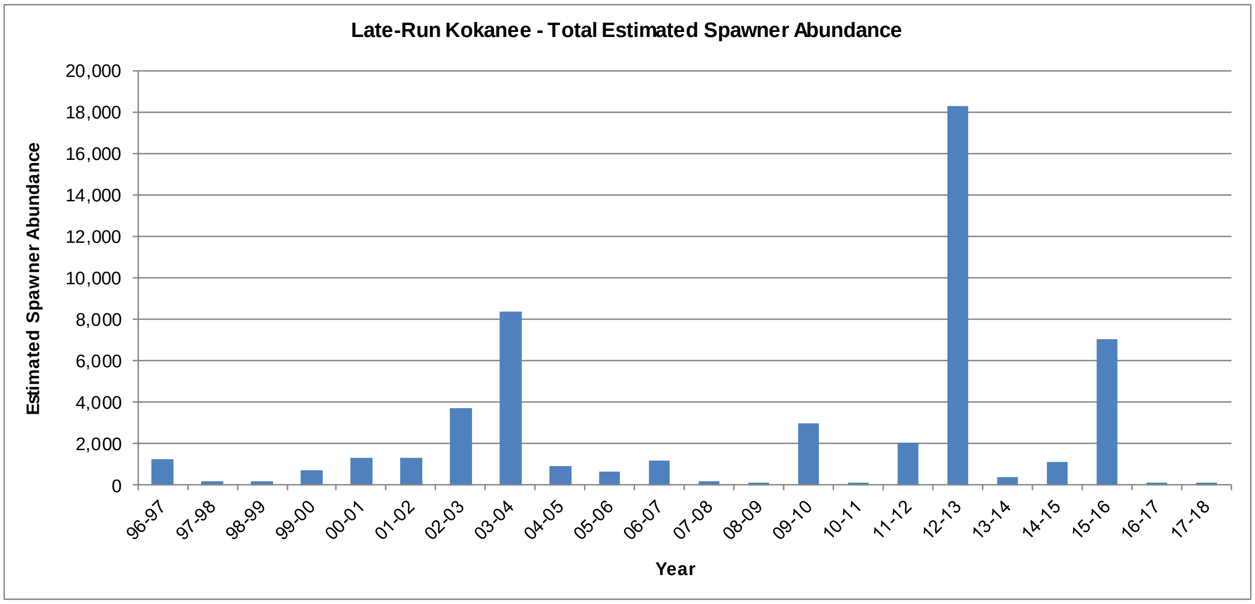

Figure 2. Lake Sammamish late-run kokanee total escapement from 1996–2018.

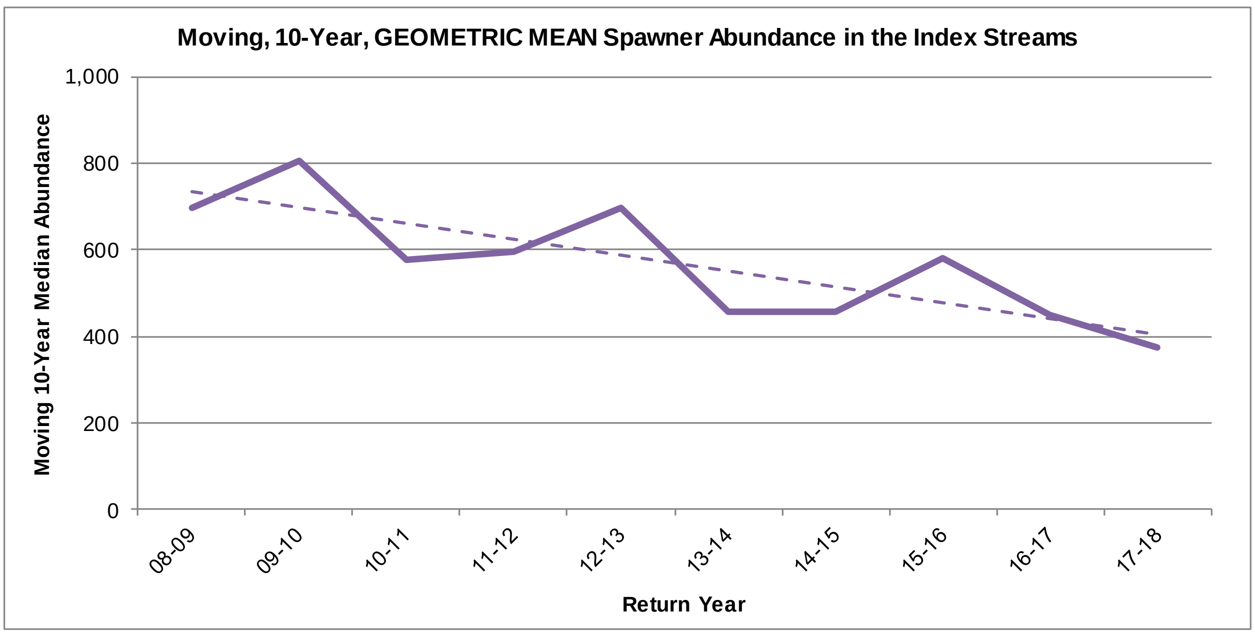

Figure 3. Time series of moving 10-year geometric mean kokanee spawner abundance in Lake Sammamish index streams, 2008–2018.

Research suggests the Lake Sammamish kokanee population may be affected by a number of chronic environmental stressors (see Lake Sammamish Kokanee Work Group, 2016). Suspected causes of decline include increased stormwater impacts on natal streams, past hatchery practices, predation, disease, fishing, passage barriers, and atypical lake temperature and DO levels.

The combination of increased lake temperature and reduced DO levels is popularly known as the “temperature-DO squeeze” (see Figure 4). During summer, layers of water are stratified by temperature at various depths. Warm water (uninhabitable to kokanee) extends downward from the surface (the epilimnion), and deepens from June through September. During this period, biological processes cause DO to decrease in the lower layers of the lake (the hypolimnion), gradually creating a zone of low DO also uninhabitable by kokanee and other salmonids. The zone between these two inhospitable layers generally corresponds to the lake metalimnion. During annual thermal stratification in Lake Sammamish, the metalimnion tends to provide the only lake habitat with the combination of temperature and DO suitable for kokanee survival, which are temperatures 17°C or below (Brett, 1971; Brett, 1976) and DO levels between about 4 to 8 mg/L (Chapman, 1986). The magnitude and duration of this annual “temperature-DO squeeze” varies among years and has likely occurred since the lake was formed after the last glaciation. In some summers, only a very small amount of suitable kokanee habitats exists. Actual observations of kokanee distribution and feeding and the magnitude and duration of “temperature-DO squeeze” during 2002 are described in Berge (2009).

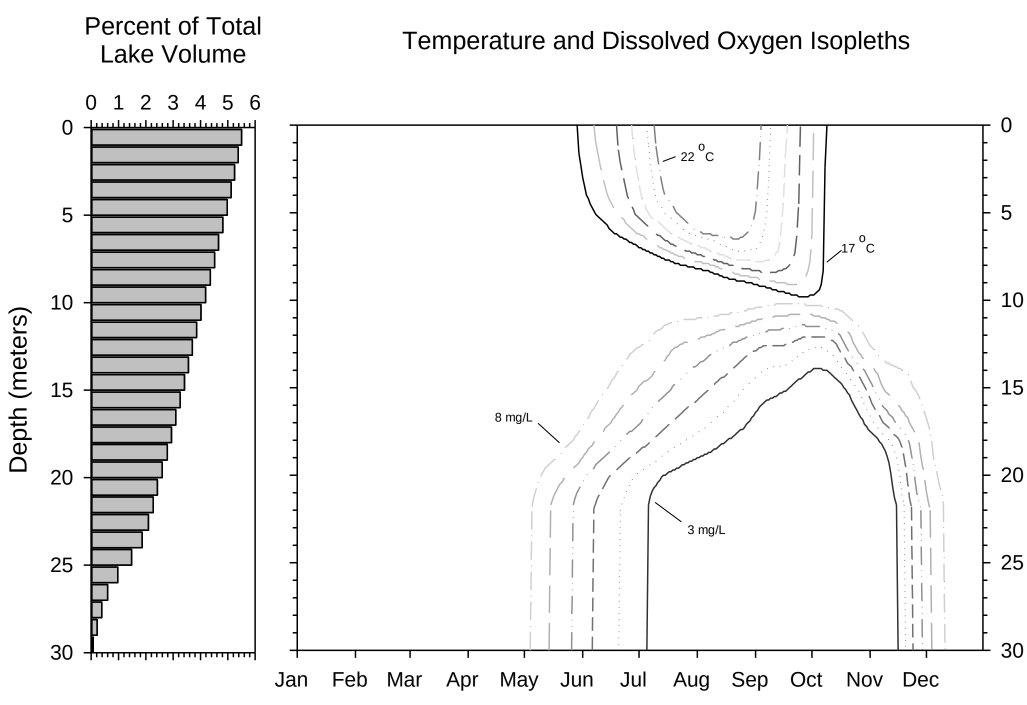

Figure 4. Isopleths of temperature and dissolved oxygen based on annual average conditions at Station 0612 between 1993 and 2017 (right panel) and relative total lake volume at 1 meter invervals (left panel).

Genetically distinct Lake Sammamish kokanee (Young et al., 2001; Young et al., 2004; Warheit and Bowman, 2008) have likely evolved to survive the thermal and DO regimes associated with the annual stratification events in the lake; however, other anthropogenic stressors may exacerbate this otherwise natural limnologic process. Chronic stressors that

may exacerbate the effects of the “temperature-DO squeeze” include possible alteration of primary and secondary productivity cycles, water quality impacts, predation by introduced species, the amplification of naturally occurring viral, bacterial, and animal parasites, and the introduction of exotic disease vectors (see Lake Sammamish Kokanee Work Group, 2016).

Strong and successive “temperature-DO squeezes” were observed in 2014, 2015, and 2016 (Figure 5). Consecutive events of this strength and magnitude appear to be atypical compared to the long-term monitoring record. Unfortunately, the stratification that occurred in 2014 and 2015 also strongly coincided with extremely low juvenile fish survival and the two lowest adult-to-adult recruitments rates observed in the last 22 years. In addition to severely constraining available habitat, these squeeze events are likely accompanied by physiologic stress, increased predation, reduced foraging opportunities, and an elevated susceptibility to viral, bacterial, and parasite related diseases.

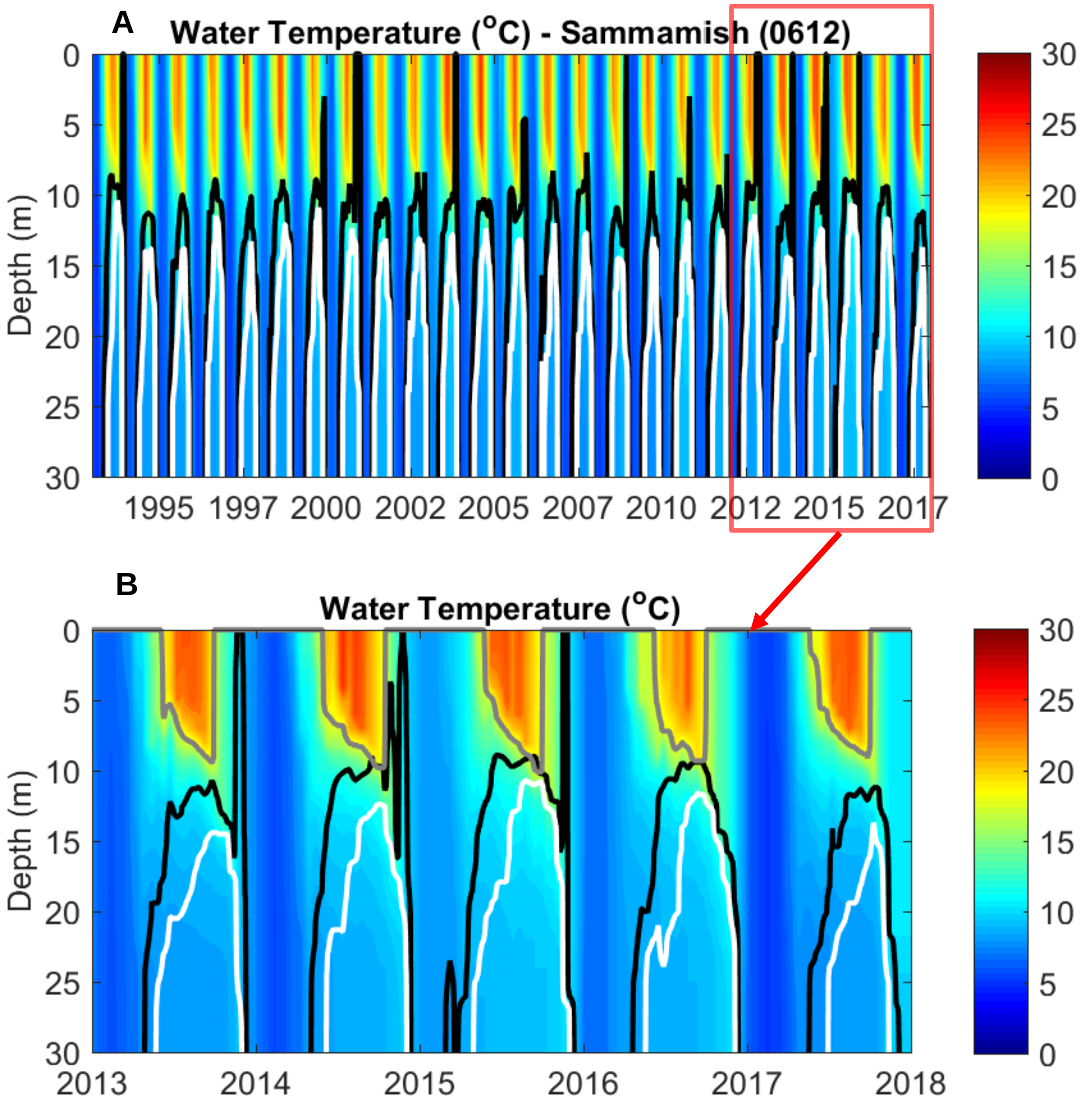

Figure 5. **Color contour plot of water temperatures observed at Station 0612 between 1993 and 2017 (A) and between 2013 and 2017. Also shown are the 4 mg/L (white line) and 8 mg/L (black line) dissolved oxygen isopleths based on data from the same station. Red box in Figure 5A is the focus of Figure 5B to illustrate the larger extent of the "DO-temperature squeeze" in 2014, 2015, and 2016. The gray line in Figure 5B is the 17°C isotherm.**

3.0. METHODS

This section describes the selection and configuration of the temperature model used in the assessment. This section also describes the temperature and dissolved oxygen monitoring data used in the assessment as well as how the monitoring data was combined with the model output to evaluate the types and amounts of kokanee habitat. The definitions and literature support for the kokanee habitat types is also provided. This section also describes two additional metrics that were evaluated (thermocline depth and the 17°C isotherm) and the tools that were used to calculate them.

3.1 Model Selection and Configuration

As part of King County's Sammamish-Washington Analysis and Modeling Program (SWAMP), a suite of models were developed. Models that were developed included an HSPF (Hydrological Simulation Program – FORTRAN) watershed hydrologic model and two dimensional (2-D) and three dimensional (3-D) hydrodynamic models of Lake Sammamish (King County, 2008; King County, 2013). A 2-D model of the Sammamish River was also developed (King County, 2009).

The Lake Sammamish 3-D model is CH3D-Z (curvilinear hydrodynamics in three dimensions, Z-grid version) and the 2-D model is CE-QUAL-W2 Version 3.5. Both of these models were coded and tested by the U.S. Army Corps of Engineers and have been used to assess a variety of hydrodynamic and water quality problems. For example, CH3D-Z has been used to simulate the hydrodynamics of Chesapeake Bay and provide the hydrodynamic input to the Chesapeake Bay water quality model (Cerco and Cole, 1993). The CHD-Z model applied to Lake Sammamish was first developed and applied to Lake Washington (Kim et al., 2006; Cerco et al., 2006). The CE-QUAL-W2 model has been used in hundreds of lake and reservoir modeling studies (Cole and Wells, 2006).[8]

More recently the 3-D and 2-D Lake Sammamish temperature models were tested and applied to the evaluation of potential global warming impacts on lake kokanee habitat (King County, 2013). The response of the two models to predicted future warming was similar. For this particular application, the 2-D model was selected for estimating the potential impacts of hypothetical summer lake withdrawals. The 2-D model was selected primarily because of the more flexible features of the CE-QUAL-W2 model that readily allow the modeling of withdrawal scenarios.[9]

For information on the development and testing of the CE-QUAL-W2 2-D Lake Sammamish model, the reader is referred to King County (2013). In summary, statistical comparisons of model output to observed temperatures indicated reasonably low bias and error. Mean bias was 0.16°C and the root mean square error (RMSE) was 1.08°C for the period 1995–

[8] CE-QUAL-W2 application history: http://www.ce.pdx.edu/w2/

[9] Version 3 of the CE-QUAL-W2 model includes the implementation of a selective withdrawal algorithm for lateral withdrawals based on withdrawal flow and vertical water density structure at the designated centerline of the withdrawal point.

2002 based on comparison to over 4,000 temperature data points collected at various locations and depths in the lake. These error statistics are similar to many other well calibrated temperature models surveyed by Arhonditsis and Brett (2004). The ultimate acceptance of a model requires the evaluation of a host of factors and no specific pass/fail criteria exist. In general, model performance was considered adequate for conducting the alternatives analyses described in this report.

The 2-D grid used in the model is illustrated in Figure 6. The lake is represented by 22 segments and vertical resolution was defined using 0.91 meter (m) thick layers resulting in a close approximation of the 3-D model vertical layering scheme. The model time step was optimized and averaged about 100 seconds in each model run, which generated 8-year simulations (1995–2002).

3.2 Model Application

As noted in the Introduction, the 2-D (and 3-D) model simulates the hydrodynamics (circulation) and temperature of the lake, but it does not simulate DO or any other water quality parameters. The development of a water quality model suitable for evaluation of withdrawal impacts on kokanee habitat was considered beyond the scope of the present study. In order to perform an initial analysis of the potential impact of the withdrawal on kokanee habitat, the temperature model results for the period 1995–2002 were combined with observed dissolved oxygen profile data.

The temperature model output from the segments representing the long term routine monitoring stations 0611 and 0612 were the focus of the analyses. These two stations were selected by Isaac et al. (1966) to represent the pelagic region of the lake as part of the initial investigation of the eutrophication of the lake conducted in 1964 and 1965. Station 0611 is located in the north end of the lake where the water depth is approximately 22 m. Station 0612 is more centrally located in deeper water (depth approximately 27 m).

Station 0612 has typically been the focus of detailed analyses, because it provides data on the conditions of almost every depth in the lake and this station has the most complete records. While King County (then Metro) began consistently sampling Station 0612 in April 1981, systematic monthly sampling at Station 0611 was not initiated until 1994. Although systematic monthly sampling at 0612 began in April 1981, with the exception of surface measurements, the temperature data are considered unreliable as they were based on samples brought to the surface for measurement. Reliable temperature profiling with a digital thermistor suspended from a cable began in 1993. Therefore, the observational data analyses in this report focus on temperature and DO data collected since 1993 at Station 0612 and data collected at Station 0611 since 1994.

The data from stations 0611 and 0612 provide somewhat independent assessments of the effect of the hypothetical withdrawal on the pelagic lake habitat where kokanee are found (Berge, 2009). Data from these two stations are relatively similar and capture the strong vertical differences in temperature and DO that occur in the lake during summer. Data from these two stations do differ subtly on occasion due to their spatial separation and depths,

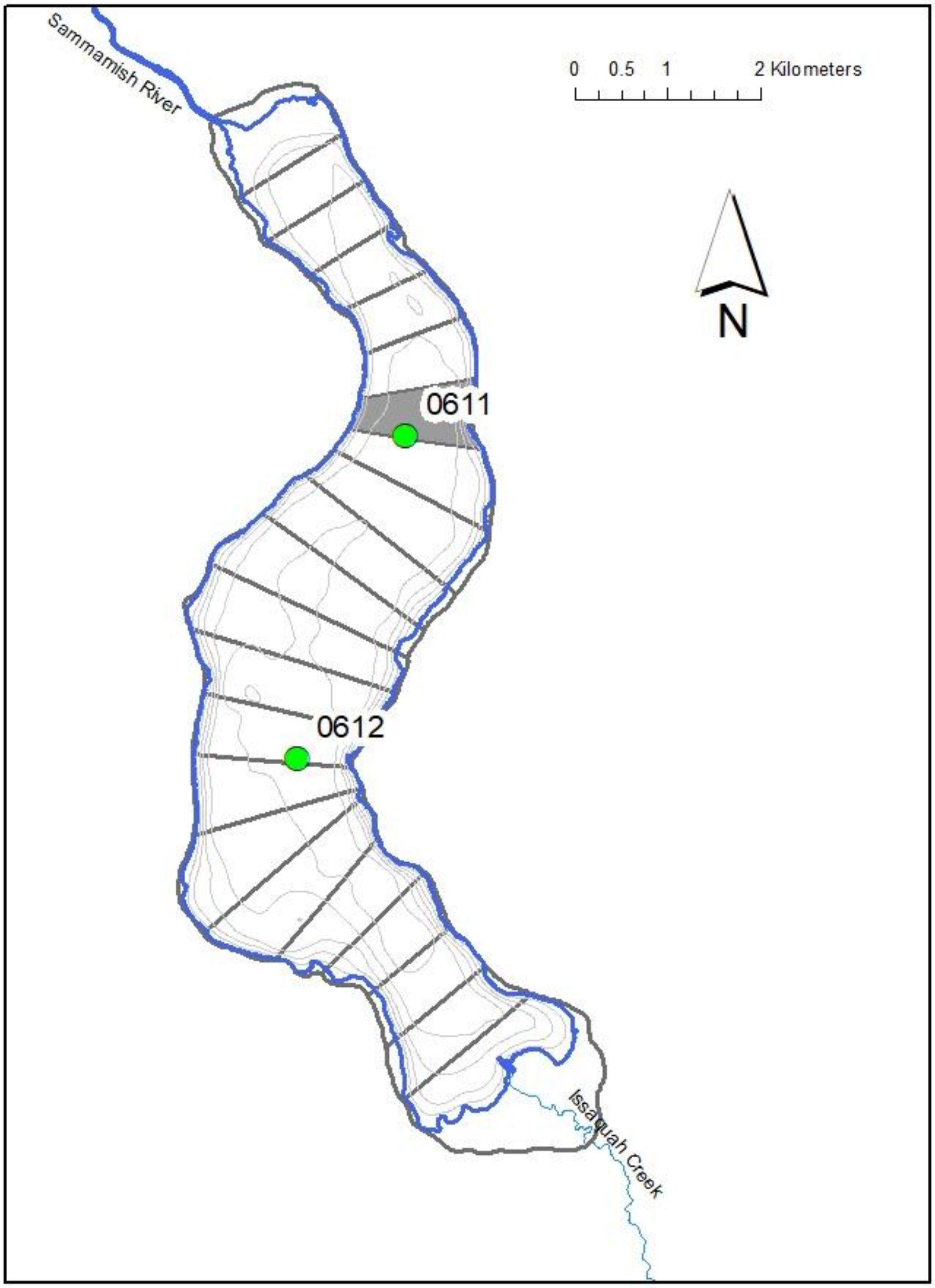

Figure 6. Map showing the longitudinal segmentation of the Lake Sammamish CE-QUAL-W2 grid and locations of routine water quality profiling stations. Major inflow (Issaquah Creek) and the lake outflow (Sammamish River) are also shown as well as the 5 meter bathymetric contour depths. The segment where the hypothetical hypolimnetic withdrawal was placed is shaded gray.

and the presence of internal seiches or waves within the lake. The similarity and differences of temperature and dissolved oxygen profiles collected from stations 0611 and 0612 for the period 1995–2002 can be seen in the plots provided in Appendix A. An evaluation of the similarity of the kokanee habitat estimates derived based on modeling and data from these two locations is also evaluated as part of this assessment.

Station 0611 is located near the proposed hypolimnetic withdrawal location (see Figure 6). The hypothetical withdrawal extends some distance south of the Sammamish weir because the north end of the lake is relatively shallow and a relatively long pipe is required to reach deeper cold water.

Model input files were developed to represent withdrawals of 10 and 20 cfs for the period July 15 through September 15 each year between 1995 and 2002. The withdrawal point was specified to take place at the 15 m depth at segment 17 which represents the model segment just north of Station 0611 (see Figure 6).

- **10 cfs Hypolimnetic Withdrawal** – Replace 10 cfs of flow to river at weir boundary with lake hypolimnetic water from the 15 m depth for the period July 15 – September 15.
- **20 cfs Hypolimnetic Withdrawal** – Replace 20 cfs of flow to river at weir boundary with lake hypolimnetic water from the 15 m depth for the period July 15 – September 15.

A **Baseline** model run representing existing lake conditions was also executed to provide a basis for comparison of the effect of each alternative to a consistent benchmark.

3.3 Estimating Effects on Lake Thermal Structure

The analytical tools developed as part of the assessment of global warming impacts on Lake Sammamish kokanee habitat (King County, 2013) were used in this study. These analytical tools evaluate the potential effects of model scenarios on lake thermal structure and kokanee habitat. Details of those methods can be found in King County (2013). The methods are briefly summarized below.

3.3.1 Lake Analyzer

Model output from the two central lake monitoring locations (stations 0611 and 0612) were processed and analyzed using Lake Analyzer (Read et al., 2011). Lake Analyzer is a Matlab program designed for analyzing high resolution lake profiling data that is also well suited to analyzing lake temperature model output. Lake Analyzer was used to calculate a number of metrics relevant to analyses of lake thermal regimes, including, but not limited to, thermocline depth and thermal resistance to mixing (Schmidt stability index). The depth of the thermocline is the depth at which maximum change in temperature with respect to change in depth occurs. The Schmidt stability index is essentially a measure of the amount of energy transfer required to completely mix a lake to a uniform density. Lake Analyzer

was also used to produce color contour plots of temperature that visually illustrated changes in lake temperature under different management scenarios.

3.3.2 17°C Isotherm

Observed temperature data and model output for the grid cells representing stations 0611 and 0612 were processed using Matlab scripts that determined the isotherms for 17°C. The 17°C threshold was identified as a kokanee avoidance threshold (i.e., kokanee avoid areas of the lake with a temperature greater than 17°C) (Kirk Krueger, WDFW, pers. comm., email, May 28, 2013).

3.3.3 Favorable Habitat Volume for Kokanee

Observed temperature and DO data collected from the central long-term monitoring stations (stations 0611 and 0612) from 1993 to 2017 were analyzed to estimate the daily volume of the lake considered to be optimal to uninhabitable habitat for kokanee as follows (strata were developed through a synthesis of species specific information from Brett [1971], Brett [1976], and Chapman [1986]):

- The volume of the lake with temperatures less than 17°C and DO greater than 8 mg/L was considered biologically **optimal** kokanee habitat.
- The volume of the lake with temperatures less than 17°C and DO between 6 and 8 mg/L was considered **sub-optimal** kokanee habitat. This strata represents habitats where kokanee begin to be affected by involuntary paralethal conditions. Paralethal conditions may include reduced swim speeds, reduced growth rates, changes to metabolism, and altered behaviors, which can lead to decreased predator avoidance and increased vulnerability to various disease vectors.
- The volume of the lake with temperatures less than 17°C and DO between 4 and 6 mg/L was considered **high risk** kokanee habitat. This strata represents habitats where kokanee are significantly affected by involuntary paralethal conditions (described above.)
- The volume of the lake with temperatures greater than 17°C and/or dissolved oxygen concentrations less than 4 mg/L was considered **uninhabitable** kokanee habitat. Studies of sockeye and other salmonids describe how conditions below 4 mg/L DO facilitate severe biological impairments, including mortality, and especially with chronic exposures greater than one day. (Chapman, 1986)

The daily values were averaged by month and evaluated graphically and statistically (non-parametric Mann-Kendall test) for trends.

The effect of the hypothetical withdrawal scenarios on kokanee habitat volume were evaluated using the modeled temperature (1995–2002) at the two model grid locations representing stations 0611 and 0612 in Lake Analyzer. Observed DO data from the two central lake monitoring stations (1995–2002) were used to include DO in the modeled kokanee habitat volume calculations, because the model only simulated temperature. The

temperature data from the model and the observed DO data were combined as described above to estimate optimal, sub-optimal, high risk, and uninhabitable kokanee habitat for the modeled baseline and withdrawal scenarios.

4.0. RESULTS

4.1 Historical Trends

Monthly average uninhabitable, high risk, sub-optimal, and optimal kokanee habitat volume for July, August, and September estimated from data collected at Station 0612 reflect the seasonal patterns in temperature and DO isopleths noted above (see Figure 4). On average, the greatest amount of high risk, sub-optimal, and optimal kokanee habitat in these three months is found in July; 13, 15, and 17 percent, respectively (Figure 7). The volumes of these habitat types decline through August and September with a minimum volume of these habitat types occurring in September; 8, 5, and 3 percent, respectively (Figure 7). The least amount of unsuitable kokanee habitat during these three months occurs in July (54 percent) and unsuitable habitat volume increases to a maximum of 84 percent in September (Figure 7). In some years there is no optimal kokanee habitat in September and less than 3 percent of the lake volume would be considered sub-optimal or high risk habitat (Figure 8). The year with the highest volume of uninhabitable habitat in September was 2015, which was recorded at both stations (Figures 8 and 9).

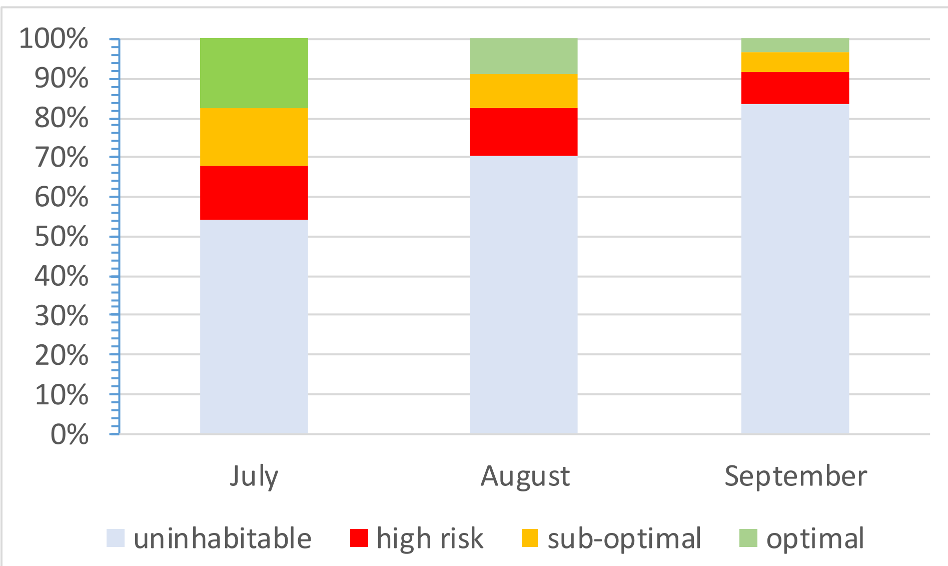

Figure 7. Average monthly mean uninhabitable, high risk, sub-optimal, and optimal kokanee habitat volume in July, August, and September as a percent of total lake volume based on data colllected at Station 0612 from 1993 to 2017.

Overall, there was a great deal of coherence between the habitat volume estimates based on the data from stations 0611 and 0612 (see Figures 8 and 9). For example, Pearson correlation coefficients for each September habitat type volume (monthly mean) between the two stations ranged from 0.74 and 0.76 for sub-optimal and high risk habitats and 0.85 and 0.89 for optimal and uninhabitable habitat types. Overall, the kokanee habitat volumes estimated from the data from stations 0611 and 0612 are of similar magnitude and the overall trends observed between the two stations were also similar. No statistically

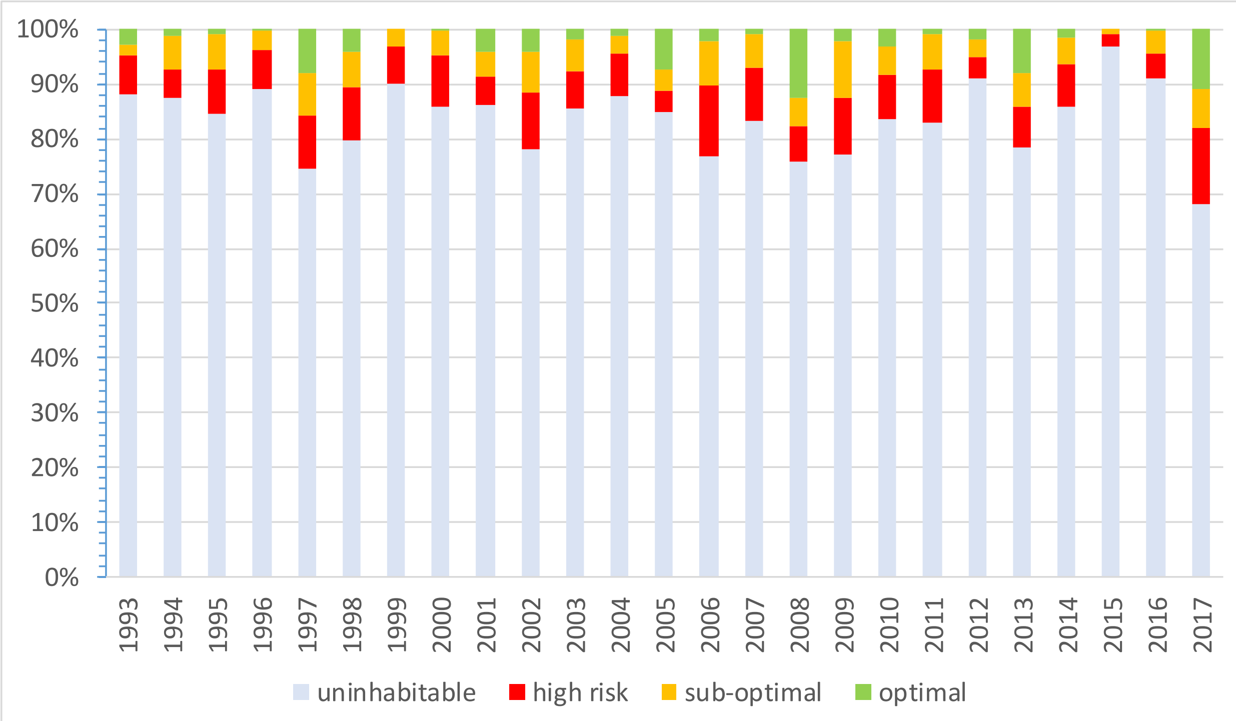

Figure 8. Monthly mean uninhabitable, high risk, sub-optimal, and optimal kokanee habitat volume in September as a percent of total lake volume based on data colllected at Station 0612 from 1993 to 2017.

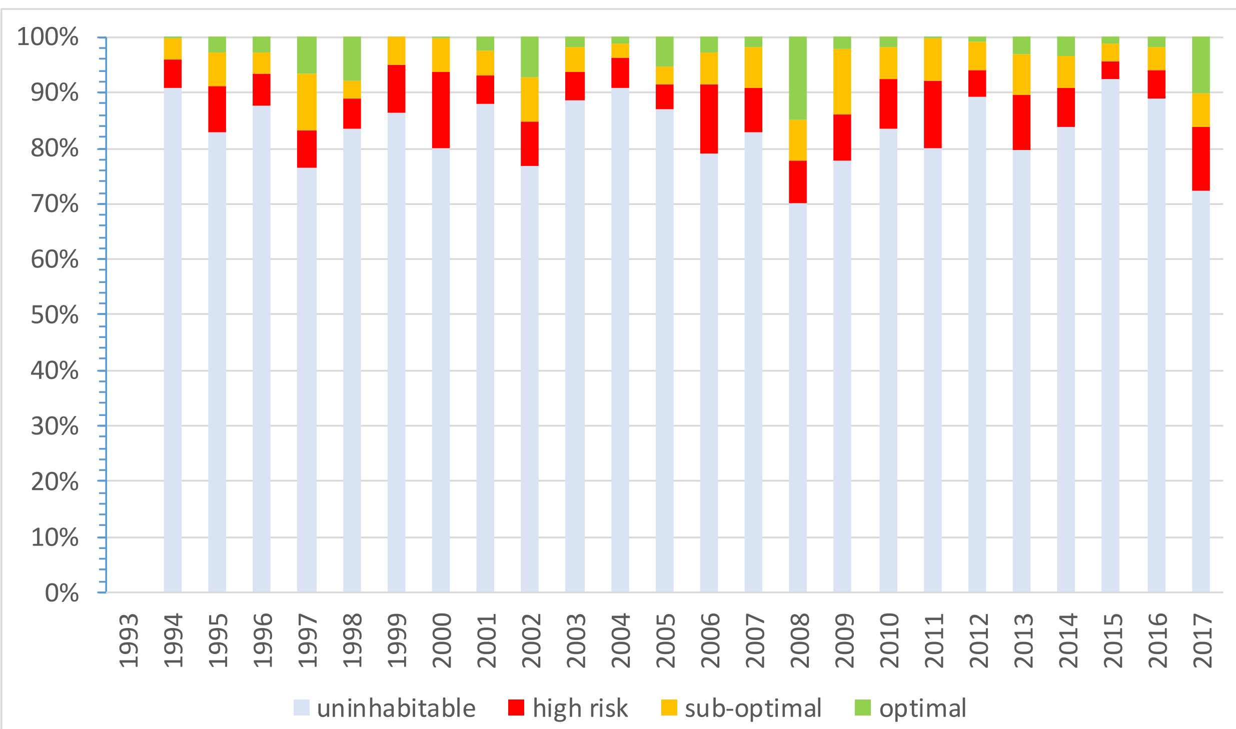

Figure 9. Monthly mean uninhabitable, high risk, sub-optimal, and optimal kokanee habitat volume in September as a percent of total lake volume based on data colllected at Station 0611 from 1994 to 2017.

significant trends ($p<0.05$) were detected for the period of record in any of the four habitat type monthly mean volumes for July, August, or September. Because the results are so similar between these two stations, and data from Station 0612 represents all depths in the lake, the results presented below focus on analyses conducted at the location representing Station 0612.

4.2 Model Results

4.2.1 Thermocline Depth

The effect of a July 15–September 15 hypolimnetic withdrawal on thermocline depth was relatively insignificant (Figure 10). The maximum differences in monthly average thermocline depth (1995–2002) occurred in September. In September, the average thermocline depth was 0.1 m deeper than the Baseline in the 20 cfs withdrawal scenario and 0.09 m deeper in the 10 cfs withdrawal scenario. These differences would not be detected by the current lake monitoring program which follows a standard protocol of measuring temperature at 1 m depth intervals.

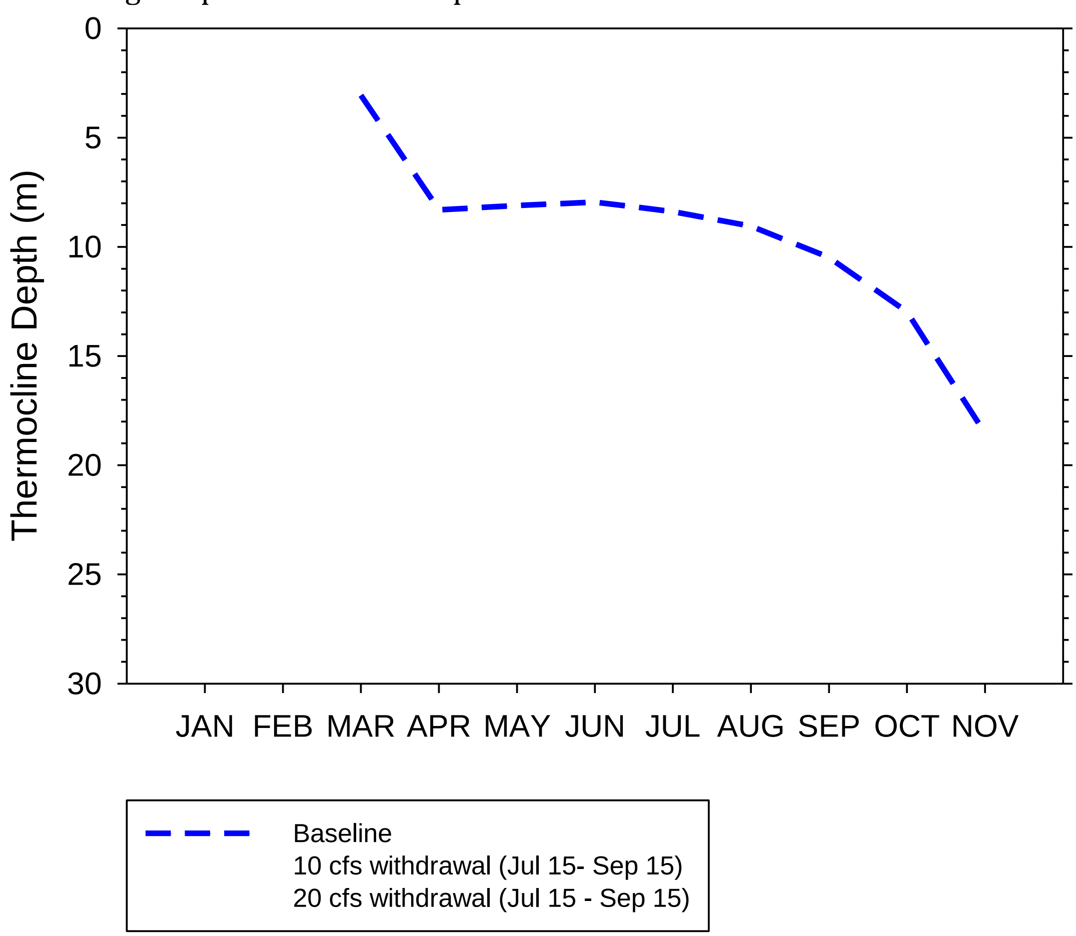

Figure 10. Monthly averaged thermocline depths based on the eight years of output from the 2-D CE-QUAL-W2 Lake Sammamish model at Station 0612.

4.2.2 Schmidt Stability

The effect of a July 15–September 15 hypolimnetic withdrawal on Schmidt stability was relatively insignificant (Figure 11). The maximum differences in monthly average Schmidt stability (1995–2002) occurred in September. In September, the average Schmidt stability was 2.2 J m^{-2} greater than the Baseline in the 20 cfs withdrawal scenario and 1.1 J m^{-2} greater in the 10 cfs withdrawal scenario. The relative magnitude of this change is less than 0.5 percent of the September mean Baseline Schmidt stability of 865.7 J m^{-2}.

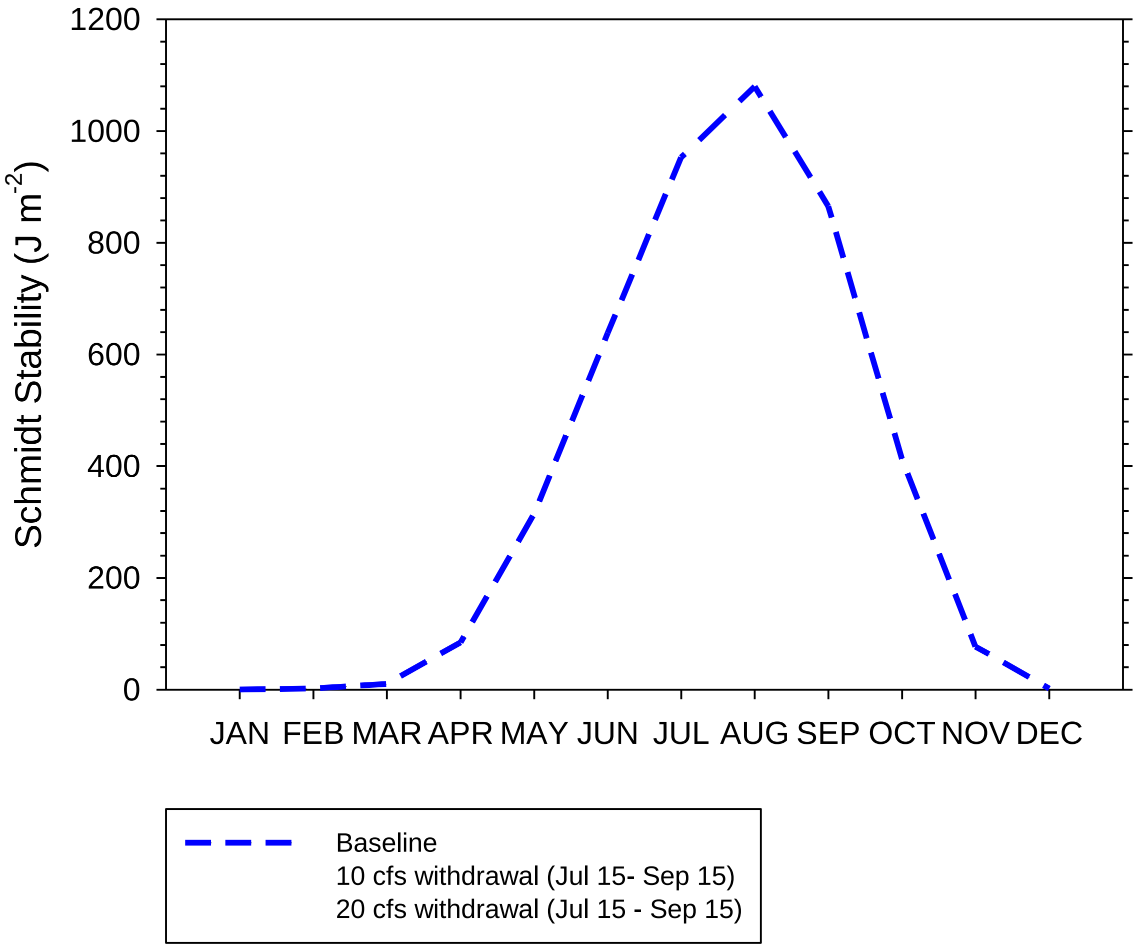

Figure 11. Monthly averaged Schmidt stability based on the eight years of output from the 2-D CE-QUAL-W2 Lake Sammamish model.

4.2.3 Color Contour Plots of Temperature

A comparison of color contour plots of temperature (1995–2002) for the model location representing Station 0612 was essentially the same for the Baseline and 20 cfs withdrawal scenarios (Figure 12).

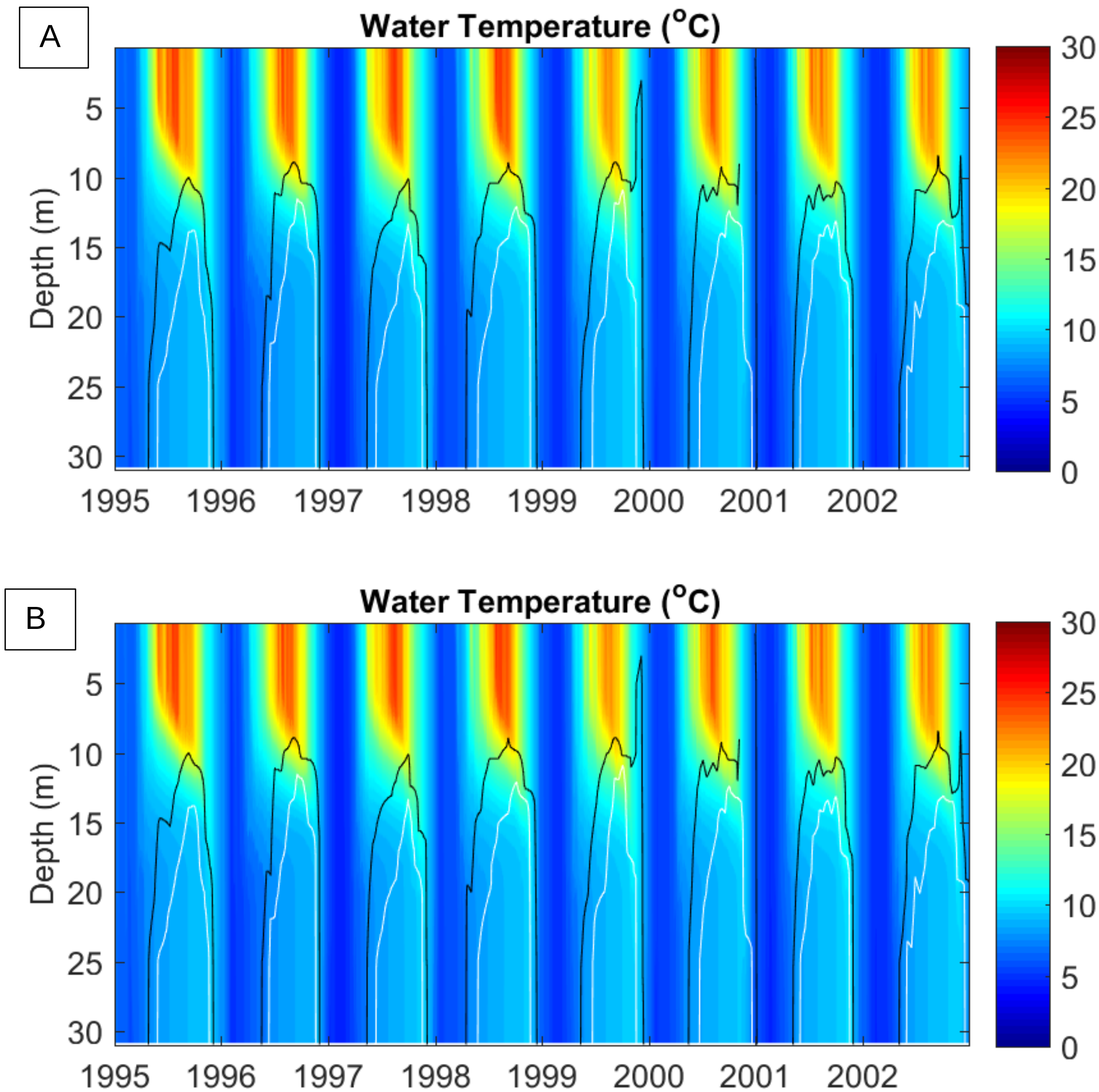

Figure 12. Color contour depth vs time (1995–2002) plots of lake temperature at the central lake station (0612) based on the 2-D model: (A) is the baseline model run, (B) is the 20 cfs hypolimnetic withdrawal scenario. Also shown are the 4 mg/L (white line) and 8 mg/L (black line) dissolved oxygen isopleths based on data from the same station.

4.2.4 17°C Isotherm

The effect of a July 15–September 15 hypolimnetic withdrawal on the depth of the 17°C isotherm was relatively insignificant (Figure 13). The maximum differences in monthly average depth of the 17°C isotherm (1995–2002) occurred in September. In September, the average depth of the 17°C isotherm was no more than 0.07 m deeper than the Baseline in the 10 and 20 cfs withdrawal scenarios. These differences would not be detected by the current lake monitoring program which follows a standard protocol of measuring temperature at 1 m depth intervals.

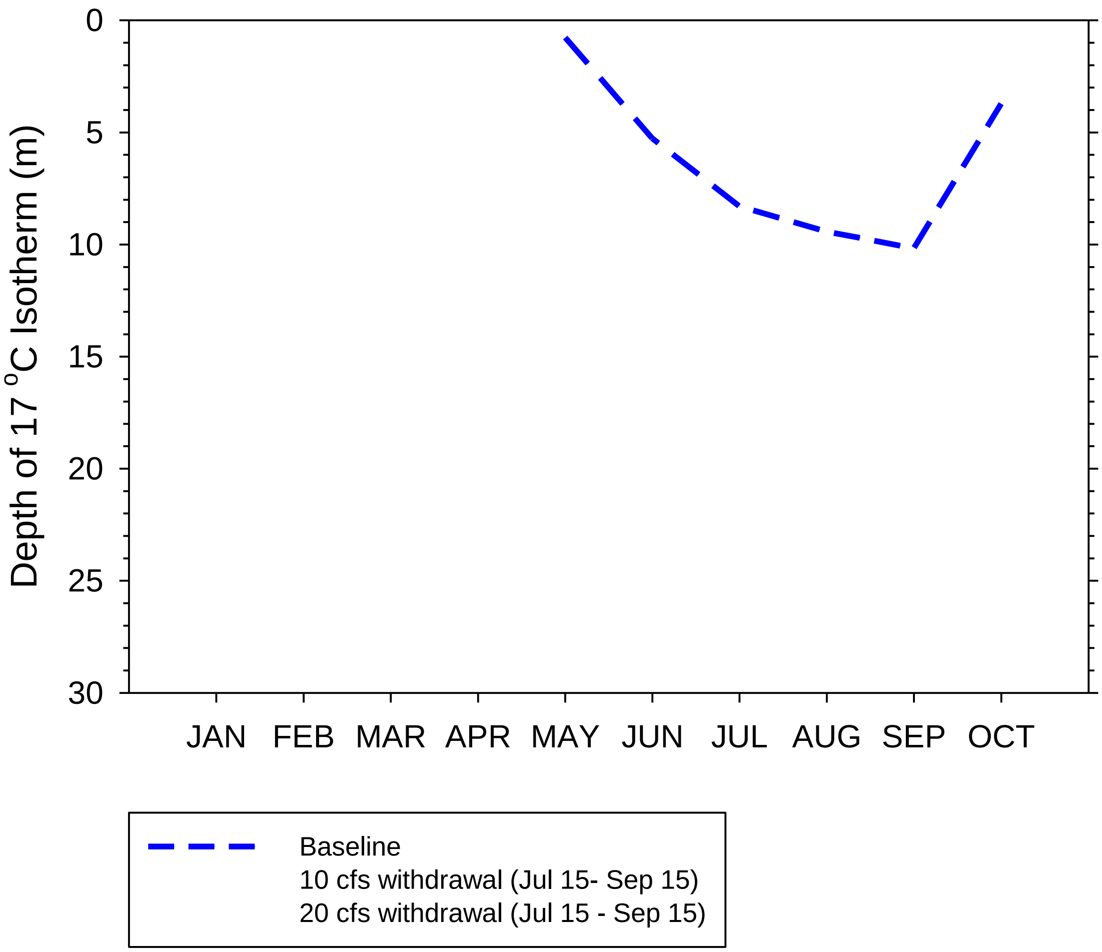

Figure 13. Monthly averaged 17°C isotherms based on the eight years of output from the 2-D CE-QUAL-W2 Lake Sammamish model.

4.2.5 Kokanee Habitat Volume

Box plots illustrating the effect of the hypothetical withdrawal on August and September (1995–2002) kokanee habitat volumes based on modeled temperature and observed DO conditions at the location represented by Station 0612 is provided in Figures 14 and 15.[10] As can be seen in Figures 14 and 15, the change in the volume of the four habitat types (uninhabitable, high risk, sub-optimal, and optimal) was small in an absolute sense. The maximum change in monthly average habitat volume measured for any habitat type was less than 0.6 percent of the total volume of the lake.

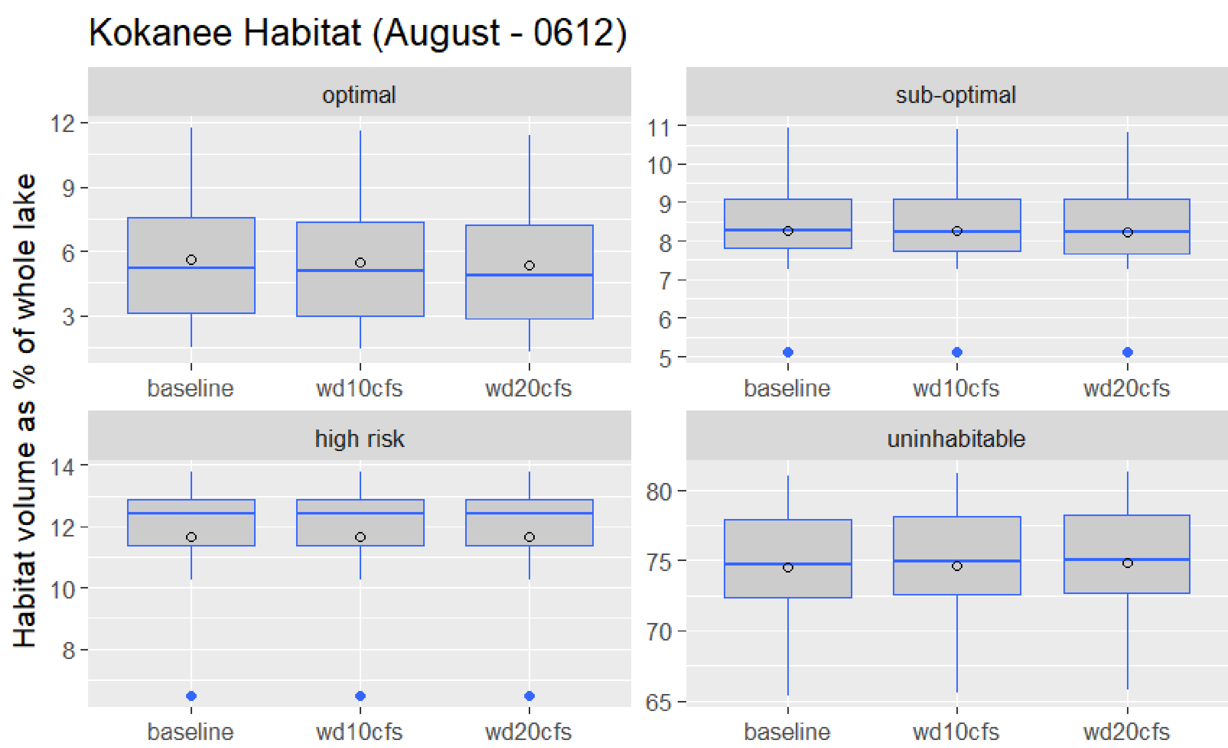

Figure 14. Station 0612 mean August (1995–2002) uninhabitable, high risk, sub-optimal, and optimal kokanee habitat volumes (shown as percent of total lake volume) for the baseline and 10 and 20 cfs withdrawal scenarios. Black circles within each box represent the mean habitat volume.

[10] Similar figures for Station 0611 are provided in Appendix B.

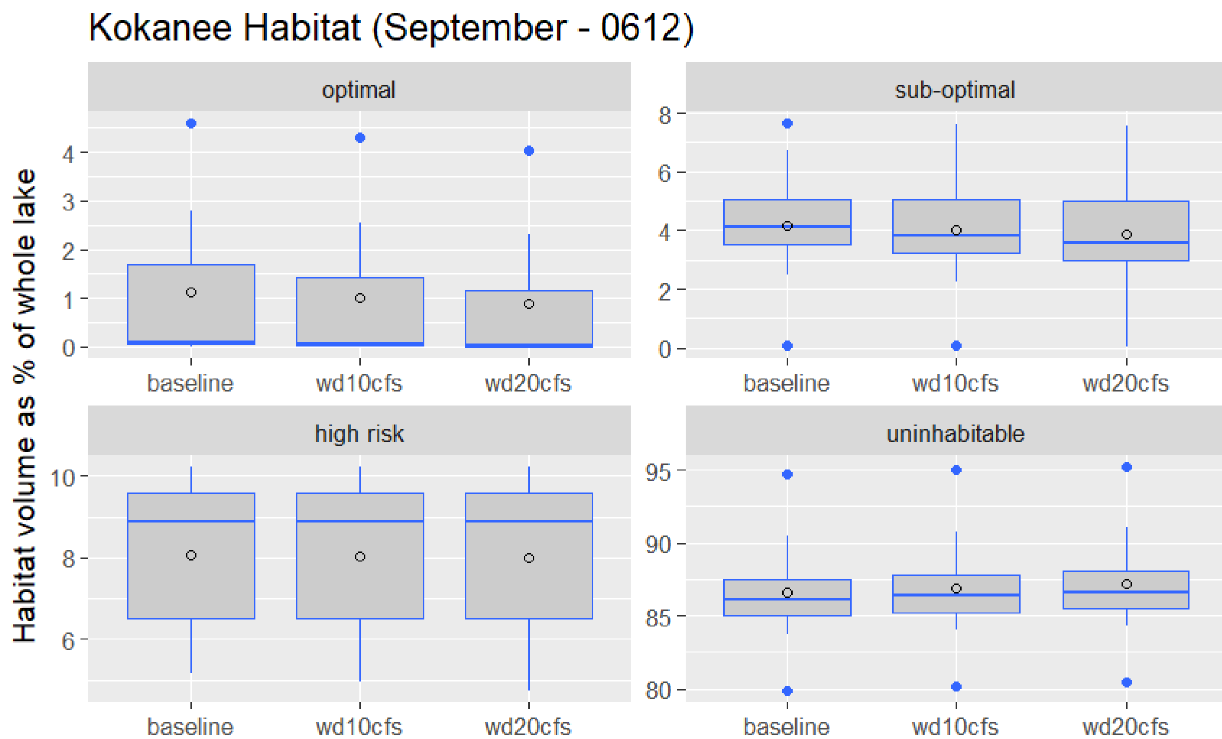

Figure 15. Station 0612 mean September (1995–2002) uninhabitable, high risk, sub-optimal, and optimal kokanee habitat volumes (shown as percent of total lake volume) for the baseline and 10 and 20 cfs withdrawal scenarios. Black circles within each box represent the mean habitat volume.

Although changes were small in an absolute sense, because the volume of high risk, sub-optimal, and optimal habitat was small relative to the total volume of the lake, particularly in September, relative changes in these habitats was more substantial. The relative percent change in uninhabitable, high risk, sub-optimal, and optimal habitat types in September based on measured changes in the mean, minimum, and maximum habitat volumes is presented in Figure 16. The largest relative change occurred in the minimum September sub-optimal habitat volume, a decrease of 33 and 59 percent as a result of the 10 and 20 cfs withdrawal scenarios, respectively. Note that no change in the minimum September optimal habitat volume could be calculated because the minimum optimal September habitat was zero in the Baseline scenario. The largest decreases in optimal September habitat was measured for the change in the mean volume; decreases of 10 and 20 percent were measured for the 10 and 20 cfs withdrawal scenarios, respectively. The maximum optimal September habitat volume was also reduced by 6 and 12 percent for the 10 and 20 cfs withdrawal scenarios. As a result of declines in optimal, sub-optimal, and high risk kokanee habitat, the uninhabitable volume of the lake in September increased less than 1 percent.

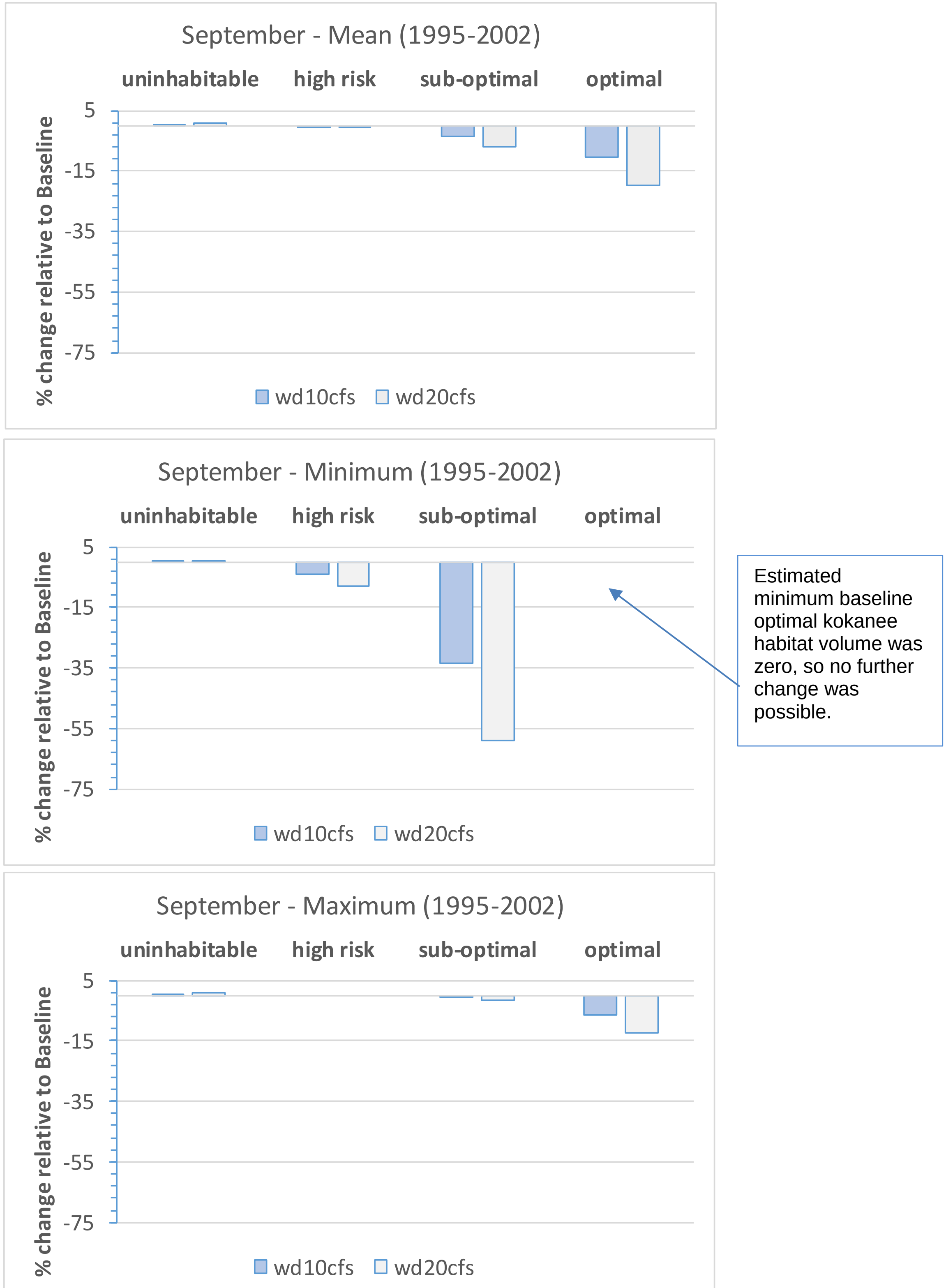

Figure 16. Percent change from the baseline scenario in the mean, minimum, and maximum (1995–2002) September uninhabitable, high risk, sub-optimal, and optimal kokanee habitat volumes at Station 0612 for the 10 and 20 cfs withdrawal scenarios.

5.0. CONCLUSIONS

The amount of estimated kokanee habitat volume under baseline conditions is relatively small during summer with the least amount of habitat found in September. In some years, there is no optimal habitat in September. The volume of the lake considered optimal habitat in September based on data collected from 1993–2017 ranged from 0 to 12 percent with an average of 3 percent.

The modeling results indicated relatively little effect on thermocline depth, thermal stability, or the depth of the 17°C isotherm. The relatively small absolute effect on lake thermal structure is likely due to selective withdrawal of a relatively small amount of cold water relative to the total volume of water below 15 m. The annual withdrawal of 20 cfs from July 15 to September 15 is conservatively estimated as no more than about 3 percent of the volume of the lake below 15 m based on the lake depth-volume relationship presented in Isaac et al. (1966).

Based on the analysis of the potential effect of the withdrawal scenarios on lake kokanee habitat, the change in the volume of the four habitat types (uninhabitable, high risk, sub-optimal, and optimal) was small in an absolute sense. The maximum change in monthly average habitat volume measured for any habitat type was less than 0.6 percent of the total volume of the lake. Although changes were small in an absolute sense, because the volume of high risk, sub-optimal, and optimal habitat was small relative to the total volume of the lake, particularly in September, relative changes in these habitats was significant.

The greatest relative change in habitat volume occurred in the minimum September sub-optimal habitat volume, a decrease of 33 and 59 percent as a result of the 10 and 20 cfs withdrawal scenarios, respectively. The greatest decreases in optimal September habitat were measured for the change in the mean volume; decreases of 10 and 20 percent were measured for the 10 and 20 cfs withdrawal scenarios, respectively. The maximum optimal September habitat volume was also reduced by 6 and 12 percent for the 10 and 20 cfs withdrawal scenarios.

The results of this analysis describe the range of effects to native Lake Sammamish kokanee habitat during peak (i.e., September) annual temperature-DO "squeeze" events. The results describe baseline conditions compared to the foreseeable effects of cold-water hypolimnetic withdrawals during that period. Baseline values (i.e., with no cold water withdrawal) indicate that Lake Sammamish kokanee are annually constrained to habitats (<17°C; >8 mg/L DO) that are approximately 0 to 12 percent of the total lake volume in September. Lake Sammamish kokanee have likely evolved with this natural range of habitat impact since the last glaciation. However, monitoring over the last 22 years indicates this population is declining, and both chronic (e.g., fish passage barriers, habitat modifications, nonnative predators, etc.) and acute (e.g., atypical bacterial, viral, and parasitic epidemics) environmental stressors are important factors in the decline. Any artificial reductions in habitats during peak (i.e., September) annual temperature-DO "squeeze" events are likely to exacerbate the effects of existing environmental stressors,

which may be both natural and anthropogenic. Considering these existing conditions, the anticipated average reductions in "optimal" (10 to 20 percent), sub-optimal, and high risk habitats under the withdrawal scenarios could have direct, indirect, and cumulative adverse impacts to the native Lake Sammamish kokanee population.

6.0. REFERENCES

Ajwani, S. 1956. A review of Lake Washington watershed, historical, biological, and limnological. MS thesis. University of Washington, Seattle, WA.

Arhonditsis, G.B. and M.T. Brett. 2004. Evaluation of the current state of mechanistic aquatic biogeochemical modeling. Mar. Ecol. Prog. Ser. 271:13-26.

Berge, H.B. 2009. Effects of a temperature-oxygen squeeze on distribution, feeding, growth, and survival of kokanee (*Oncorhynchus nerka*) in Lake Sammamish, Washington. MS Thesis, School of Aquatic and Fisheries Sciences, University of Washington. 84 p.

Berge, H.B. and K. Higgins. 2003. The current status of kokanee in the greater Lake Washington watershed. King County Department of Natural Resources and Parks, Water and Land Resources Division, Seattle, Washington. 50 p.

Berge, H.B., M.L. Hammer, and S.R. Foley. 2006. Timing, abundance, and population characteristics of spawning Chinook salmon in the Cedar/Sammamish watershed. King County Water and Land Resources Division and Washington Department of Fish and Wildlife, Region 4. http://your.kingcounty.gov/dnrp/library/2006/kcr1960.pdf

Brett, J.R. 1971. Energetic Responses of Salmon to Temperature. A Study of Some Thermal Relations in the Physiology and Freshwater Ecology of Sockeye Salmon (*Oncorhynchus nerka*). American Zoologist 11(1): 99-113.

Brett, J.R. 1976. Feeding metabolic rates of young sockeye salmon, *Oncorhynchus nerka*, in relation to ration level and temperature. British Columbia Canada Department of the Environment, Fisheries and Marine Service, Nanaimo, BC.

Cardno. 2017. 2016 Upper Sammamish River Pre-Spawn Mortality Data Report. Sammamish River Pre-Spawn Mortality Study. Prepared for King County Department of Natural Resources and Parks, Seattle, WA. Cardno, Seattle, WA.

Cerco, C.F. and T.M. Cole. 1993. Three-dimensional eutrophication model of Chesapeake Bay. Journal of Environmental Engineering 119:1006-1025.

Cerco, C.F., M.R. Noel and S.-C. Kim. 2006. Three-dimensional management model for Lake Washington, Part II: Eutrophication modeling and skill assessment. Lake and Reservoir Management 22:115-131.

Chapman, G. 1986. Ambient Water Quality Criteria for Dissolved Oxygen. US Environmental Protection Agency, Narragansett, RI.

Chin, D., W. Mansfield, M. Bowles, W.L. O'Rollins and J. Bethel. 2003. Draft. Conceptual Proposal. Enhancing Habitat Conditions at the Sammamish River Transition Zone, Marymoor Park, King County, WA.

Chrzastowski, M. 1983. Historical changes to Lake Washington and route of the Lake Washington Ship Canal, King County, WA. U.S. Geological Survey, Water Resources Investigation Open File Report 81-1182.

Cole, T.M. and S.A. Wells. 2006. CE-QUAL-W2: A two-dimensional laterally averaged, hydrodynamic and water quality model, version 3.5. Instruction Report EL-06-1, U.S. Army Engineering and Research Development Center, Vicksburg, MS.

Collins, B. 2001. Channel meander investigation for proposed Sammamish River restoration project at Marymoor Park, Washington. Memo to Doug Chin, King County, October 15, 2001. Geomorphologist, University of Washington, Earth and Space Sciences, Seattle, WA.

Feist, B.E., E.R. Buhle, D.H. Baldwin, J.A. Spromberg, S.E. Damm, J.W. Davis, and N.L. Scholz. 2018. Roads to ruin: conservation threats to a sentinel species across an urban gradient. Ecological Applications 2:2382-2396.

Fresh, K.L., E. Warner, R. Tabor, and D. Houck. 1999. Migratory behavior of adult Chinook salmon spawning in the Lake Washington watershed in 1998 as determined with ultrasonic telemetry. Draft progress report.

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, Washington.

Kim, S.-C., C.F. Cerco and B.H. Johnson. 2006. Three-dimensional management model for Lake Washington, Part I: Introduction and hydrodynamic modeling. Lake and Reservoir Management 22:103-114.

King County. 2003. King County Watershed Modeling Services – Green River Water Quality Assessment, and Sammamish-Washington Analysis and Modeling Program Watershed Modeling Calibration Report. In Progress. Prepared by Aqua Terra Consultants in conjunction with King County Water and Land Resources Division, Seattle, WA. http://www.kingcounty.gov/environment/watersheds/green-river/watershed-quality-assessment.aspx (see documents below Modeling heading)

King County. 2008. Development of a 3-dimensional hydrodynamic model of Lake Sammamish. Prepared by Curtis DeGasperi, Water and Land Resources Division. Seattle, Washington. http://www.kingcounty.gov/environment/waterandland/lakes/lakes-of-king-county/sammamish/3D-hydrodynamic-model-lake-sammamish.aspx

King County. 2009. Development of a laterally averaged 2-dimensional water quality model of the Sammamish River. Prepared by Curtis DeGasperi, Water and Land Resources Division. Seattle, Washington. http://green.kingcounty.gov/WLR/Waterres/StreamsData/reports/Sammamish-river-report.aspx

King County. 2013. Predicting Climate Change Effects on Kokanee Habitat Suitability in Lake Sammamish, Washington. Prepared by Curtis DeGasperi, Water and Land Resources Division. Seattle, Washington. http://www.kingcounty.gov/environment/animalsAndPlants/salmon-and-trout/kokanee/documents/climate-change-kokanee-habitat.aspx

King County and USACOE. 2002. Sammamish River Corridor Action Plan Final Report. Prepared by Tetra Tech, Inc. for the U.S. Army Corps of Engineers Seattle District and King County Water and Land Resources Division, Seattle, WA. http://green2.kingcounty.gov/sciencelibrary/Document.aspx?ArticleID=107

Lake Sammamish Kokanee Workgroup. 2016. Ecological Survey of "Late-Run" Kokanee in Lake Sammamish, 2016. King County, Washington.

Martz, M., M. Valentine, and C. Fitzgerald. November 1999. Sammamish River temperature study, 1998 results from temperature modeling and literature review of temperature effects on fish. Seattle District, U.S. Army Corps of Engineers.

McIntyre, J.K., J.I. Lundin, J.R. Cameron, M.I. Chow, J.W. Davis, J.P. Incardona, and N.L. Scholz. 2018. Interspecies variation in the susceptibility of adult Pacific salmon to toxic urban stormwater runoff. Environmental Pollution 238:196-203.

Müller, B., L.D. Bryant, A. Matzinger, and A. Wüest. 2012. Hypolimnetic oxygen depletion in eutrophic lakes. *Environmental Science and Technology* 46:9964-9971.

NHC. 1992. Sammamish River Multi-objective River Corridor Management Plan. Impacts of Environmental Enhancements on Water Surface Profiles. Prepared for King County Division of Surface Water Management, Seattle, WA. Northwest Hydraulic Consultants, Inc., Kent, WA.

R2 Resource Consultants. 2015. Salmonid Pre-Spawn Mortality Study; Sammamish River, King County, Washington. Prepared for King County Department of Natural Resources and Parks. Redmond, WA.

Read, J.S., D.P. Hamilton, I.D. Jones, K. Muraoka, L. Winslow, R. Kroiss, C.H. Wu and E. Gaiser. 2011. Derivation of lake mixing and stratification indices from high-resolution lake buoy data. Environmental Modeling & Software 26:1325-1336.

SPU and USACOE. 2008. Synthesis of Salmon Research and Monitoring. Investigations Conducted in the Western Lake Washington Basin. Seattle Public Utilities and U.S. Army Corps of Engineers Seattle District, Seattle, WA. http://www.govlink.org/watersheds/8/pdf/LWGI_SalmonSyn123108.pdf

Strange, J. 2007. Adult Chinook Salmon Migration in the Klamath River Basin: 2005 Sonic Telemetry Study Final Report. Yurok Tribal Fisheries Program and University of Washington School of Aquatic Fisheries Sciences in collaboration with Hoopa Valley Tribal Fisheries. https://www.fws.gov/yreka/Final-Reports/rmaap/2005-FP-01-YT-HVT.pdf

Warheit, K.I. and C. Bowman. 2008. Genetic structure of kokanee (*Oncorhynchus nerka*) spawning in tributaries of Lake Sammamish, Washington. Synthesis Report 37 January 21, 2009. Submitted to King County Department of Natural Resources and Parks, Water and Land Resources Division and Trout Unlimited – Bellevue/Issaquah, WA. 49 p.

Young, S.F., M.R. Downen, and J.B. Shaklee. 2001. A microsatellite DNA based characterization of Lake Washington/Lake Sammamish kokanee and sockeye salmon, with notes on distribution, timing, and morphology. Washington Department of Fish and Wildlife, Olympia, WA.

Young, S.F., M.R. Downen, and J.B. Shaklee. 2004. Microsatellite DNA data indicate distinct native populations of kokanee, *Oncorhynchus nerka*, persist in the Lake Sammamish Basin, Washington. Environ. Biol. Fishes 69:63-79.

This page intentionally left blank

Appendix A: Temperature and Dissolved Oxygen Profile Plots (1995–2002)

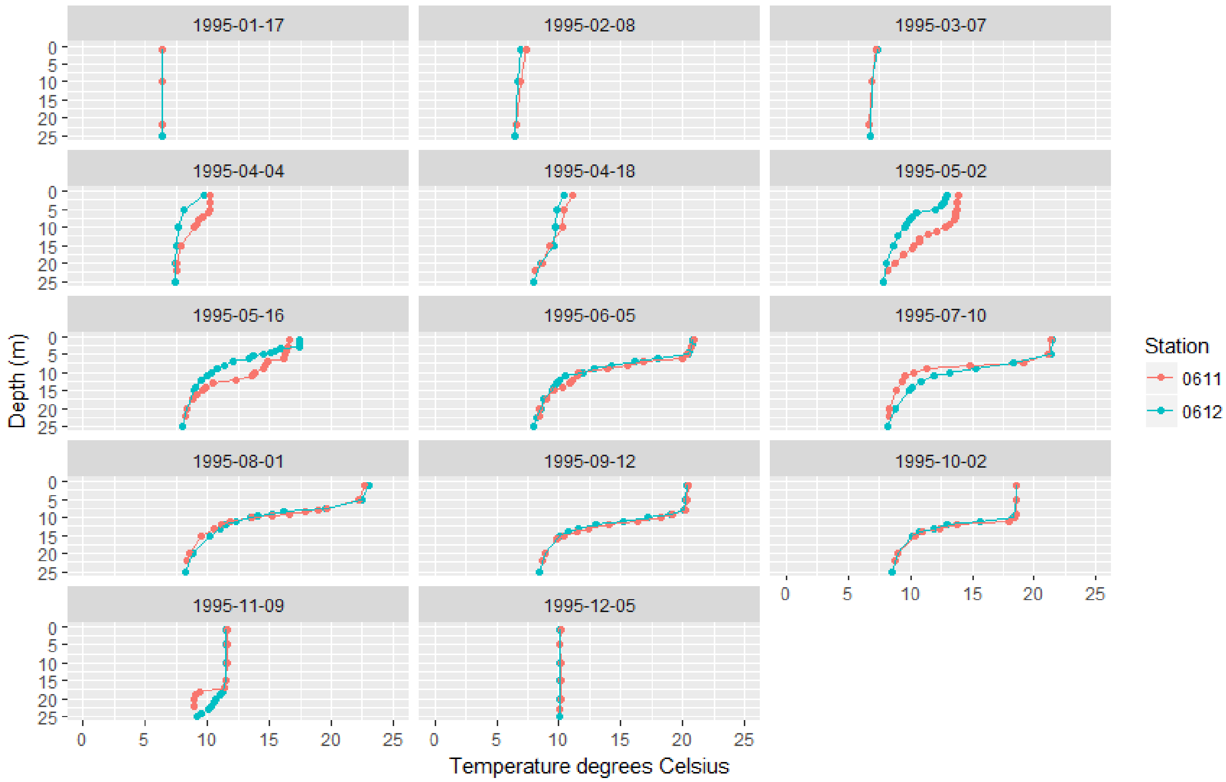

Figure A-1 Lake Sammamish temperature profiles at stations 0611 and 0612 in 1995.

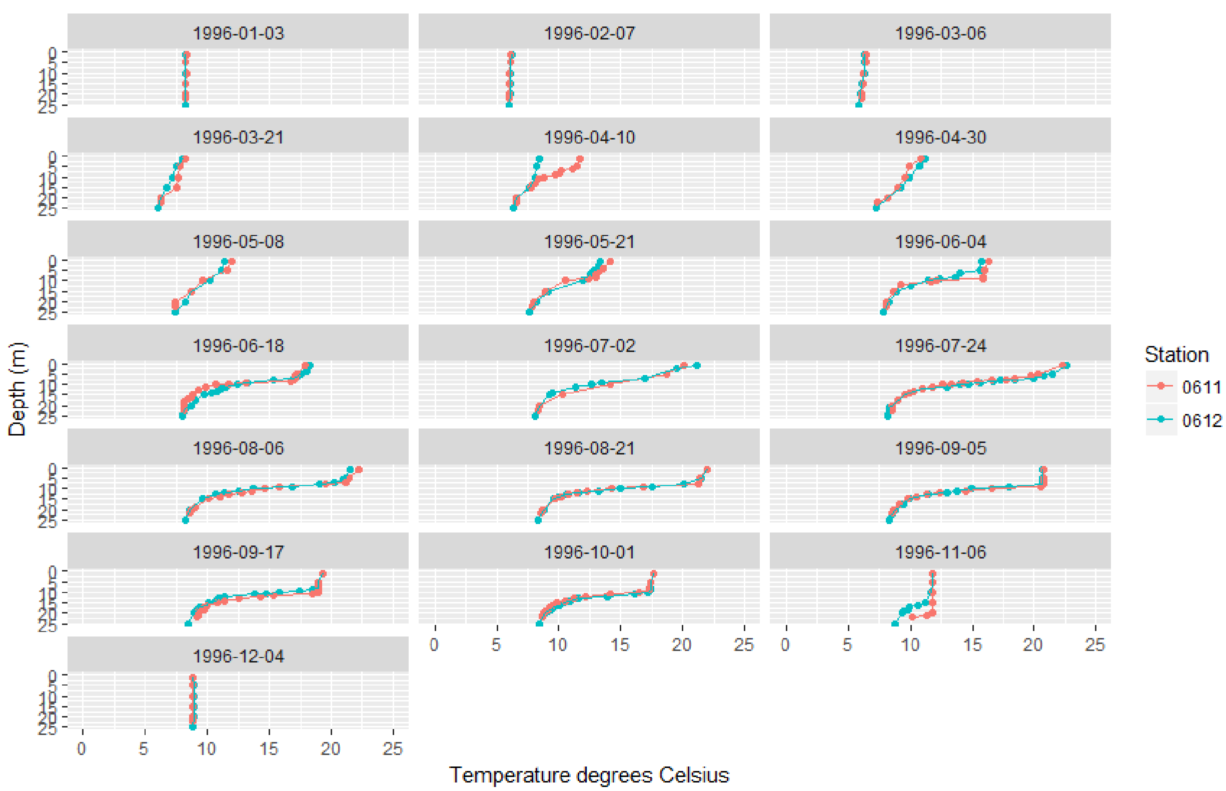

Figure A-2 Lake Sammamish temperature profiles at stations 0611 and 0612 in 1996.

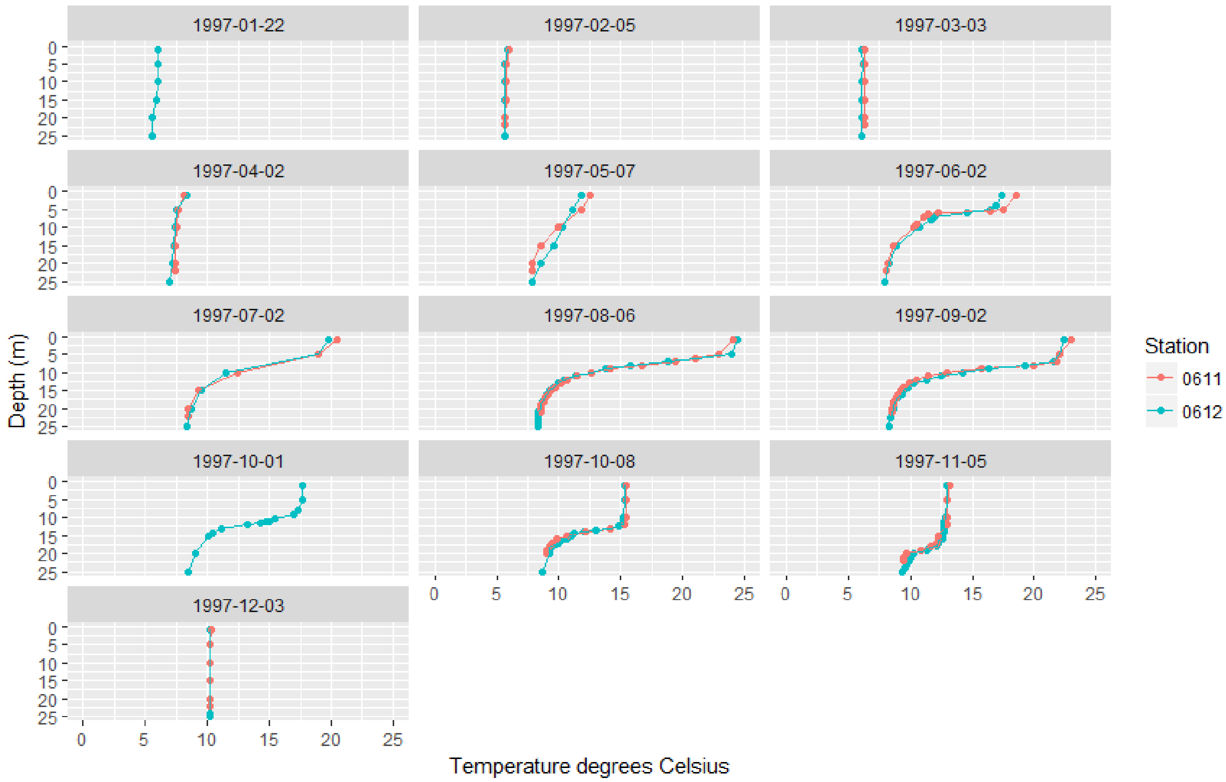

Figure A-3 Lake Sammamish temperature profiles at stations 0611 and 0612 in 1997.

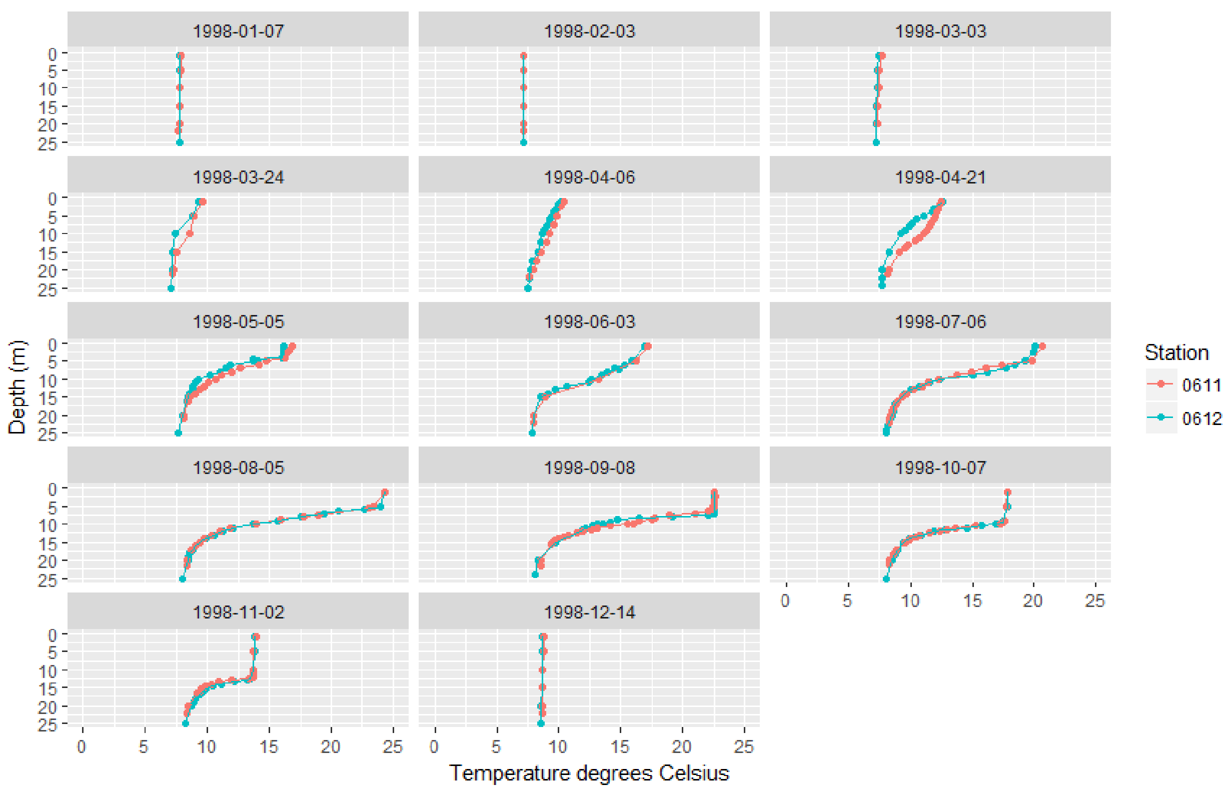

Figure A-4 Lake Sammamish temperature profiles at stations 0611 and 0612 in 1998.

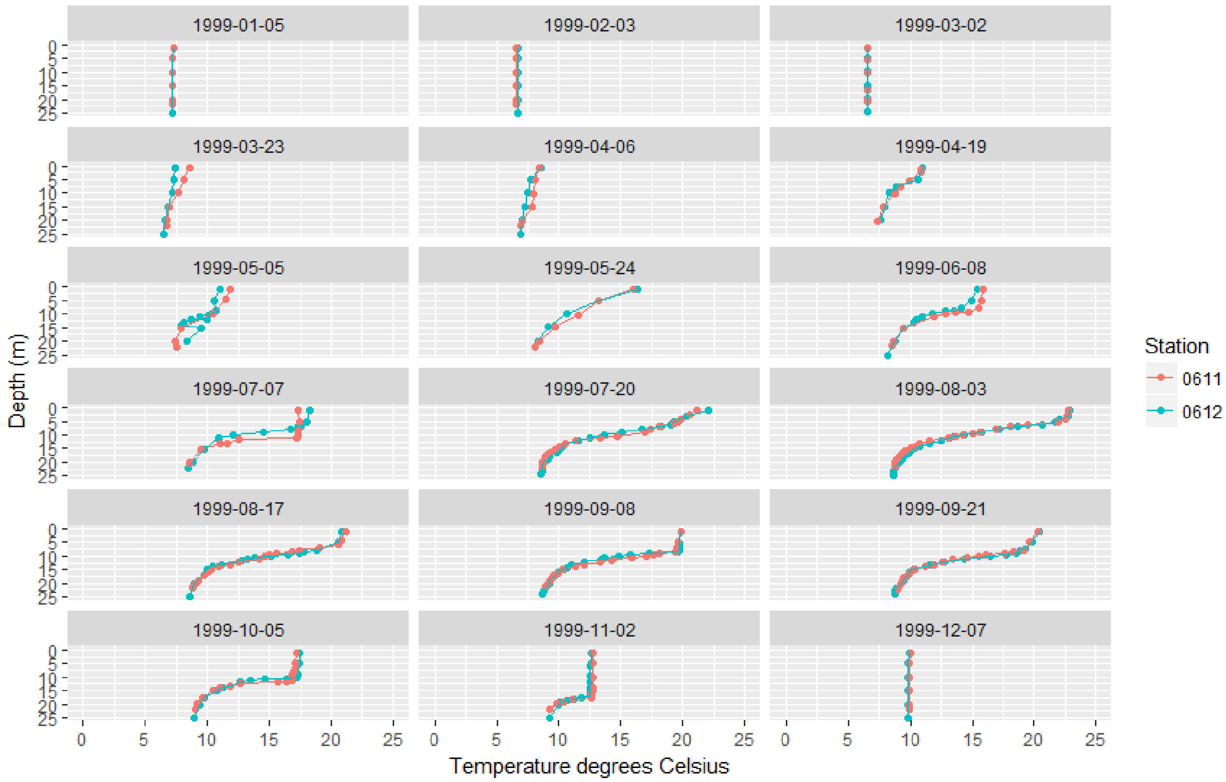

Figure A-5 Lake Sammamish temperature profiles at stations 0611 and 0612 in 1999.

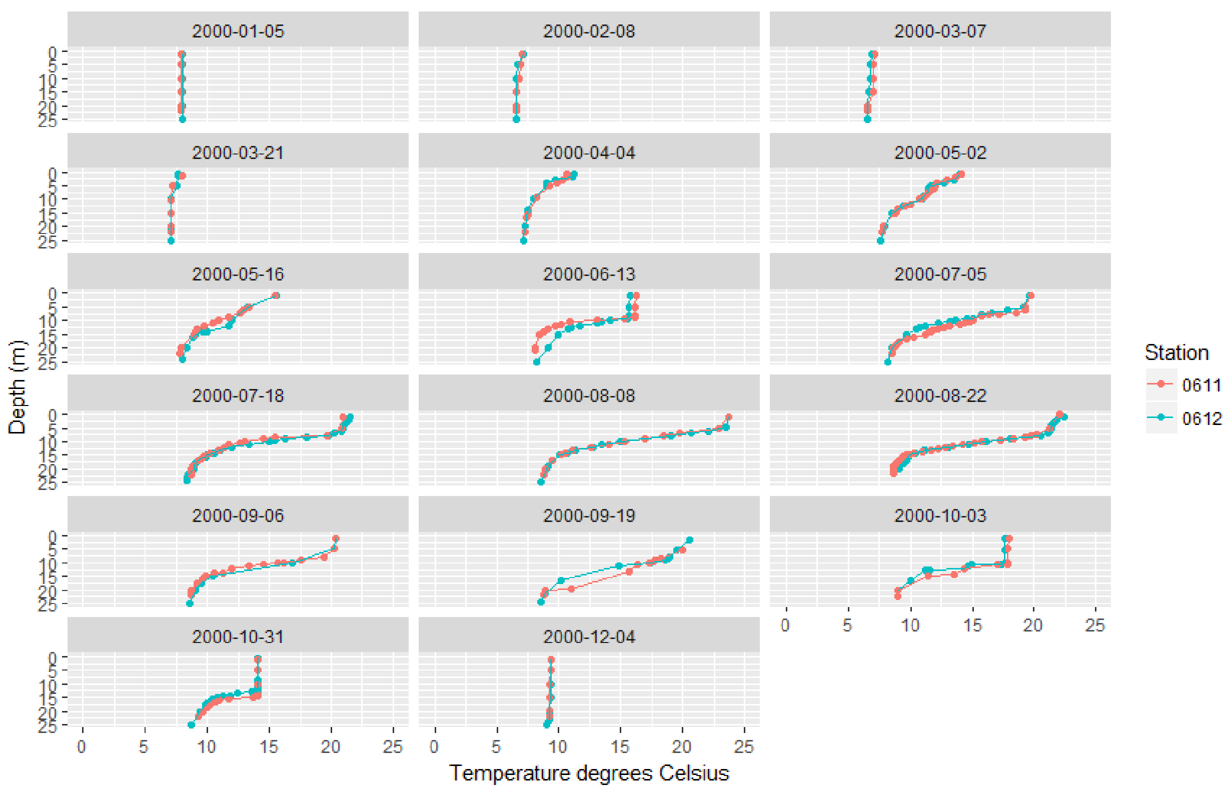

Figure A-6 Lake Sammamish temperature profiles at stations 0611 and 0612 in 2000.

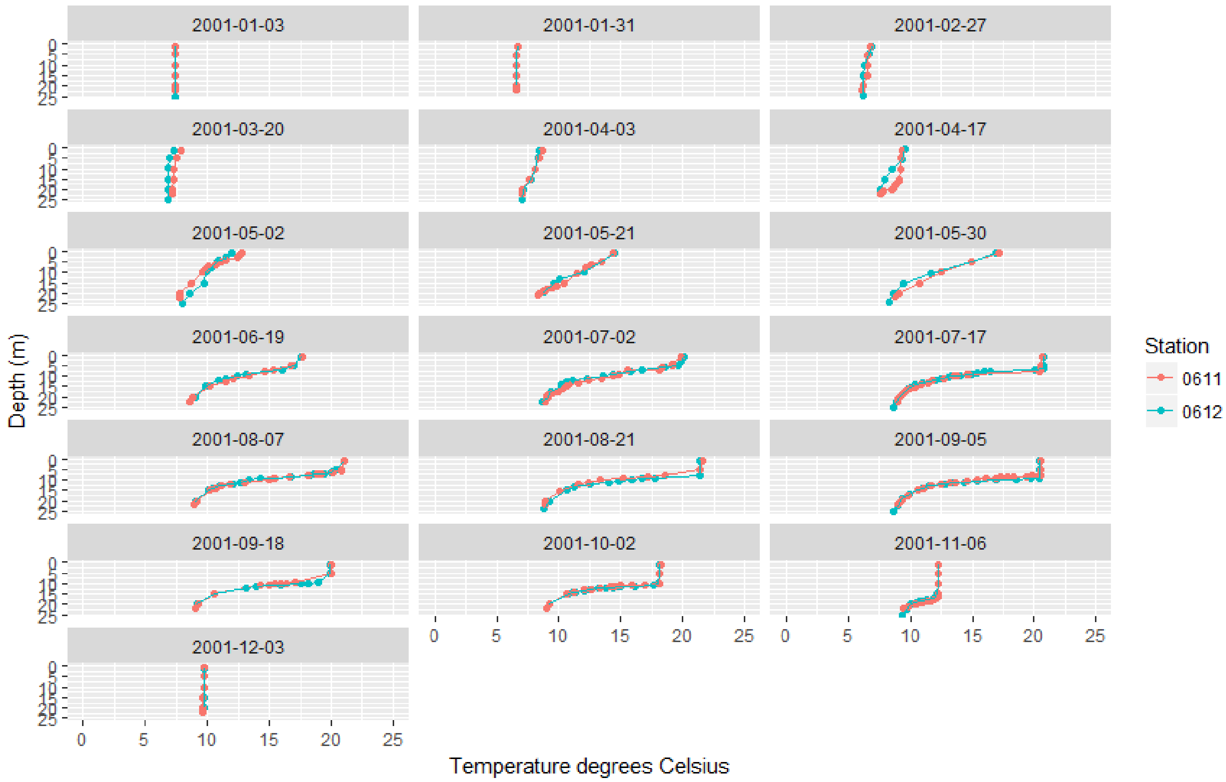

Figure A-7 Lake Sammamish temperature profiles at stations 0611 and 0612 in 2001.

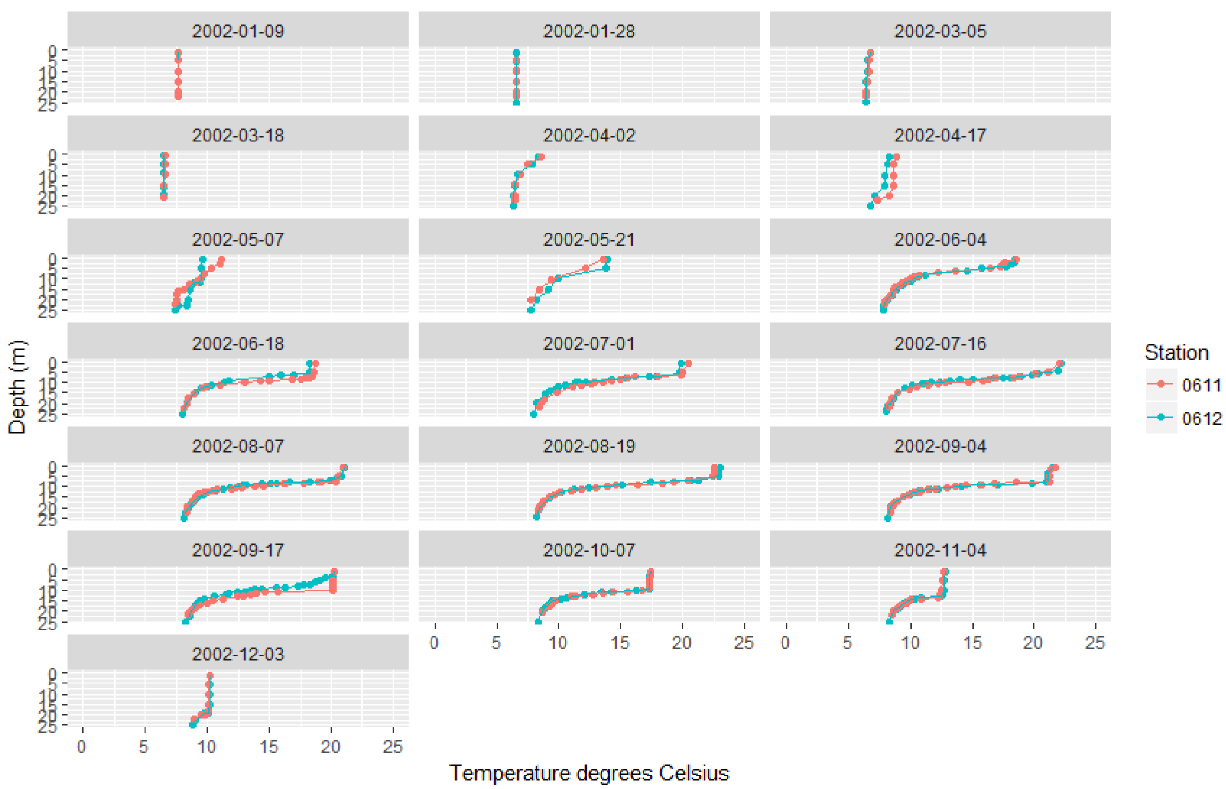

Figure A-8 Lake Sammamish temperature profiles at stations 0611 and 0612 in 2002.

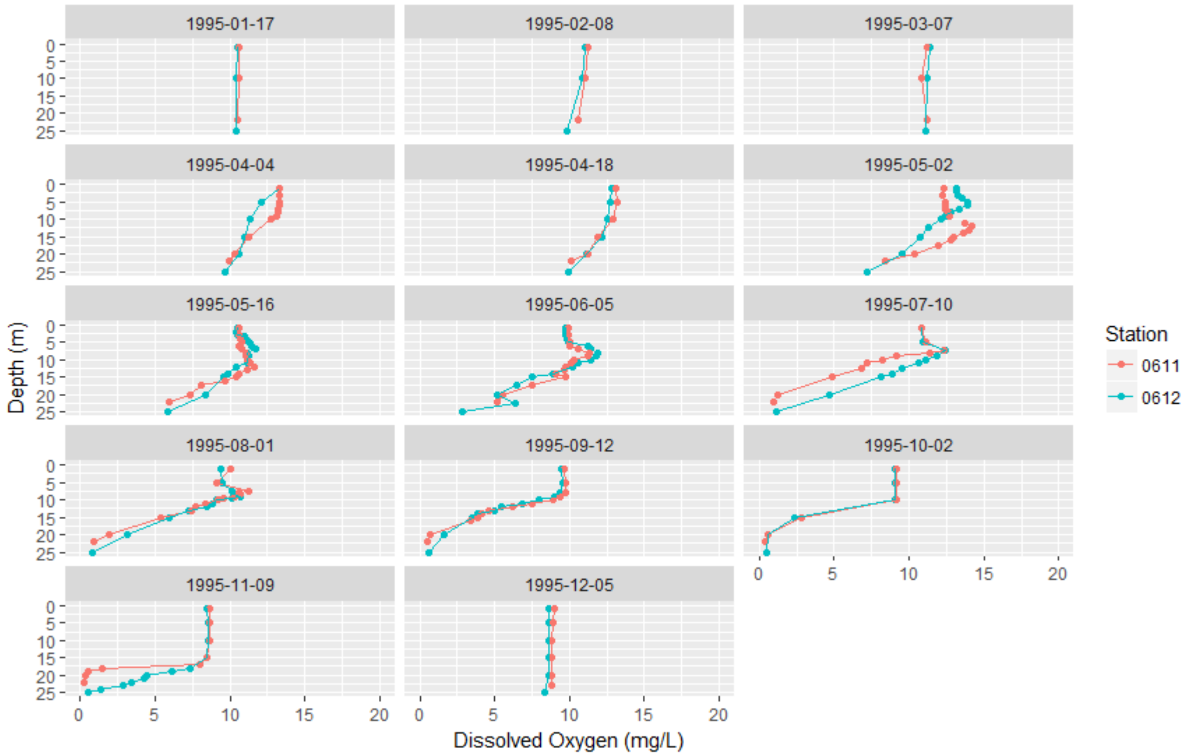

Figure A-9 Lake Sammamish dissolved oxygen profiles at stations 0611 and 0612 in 1995.

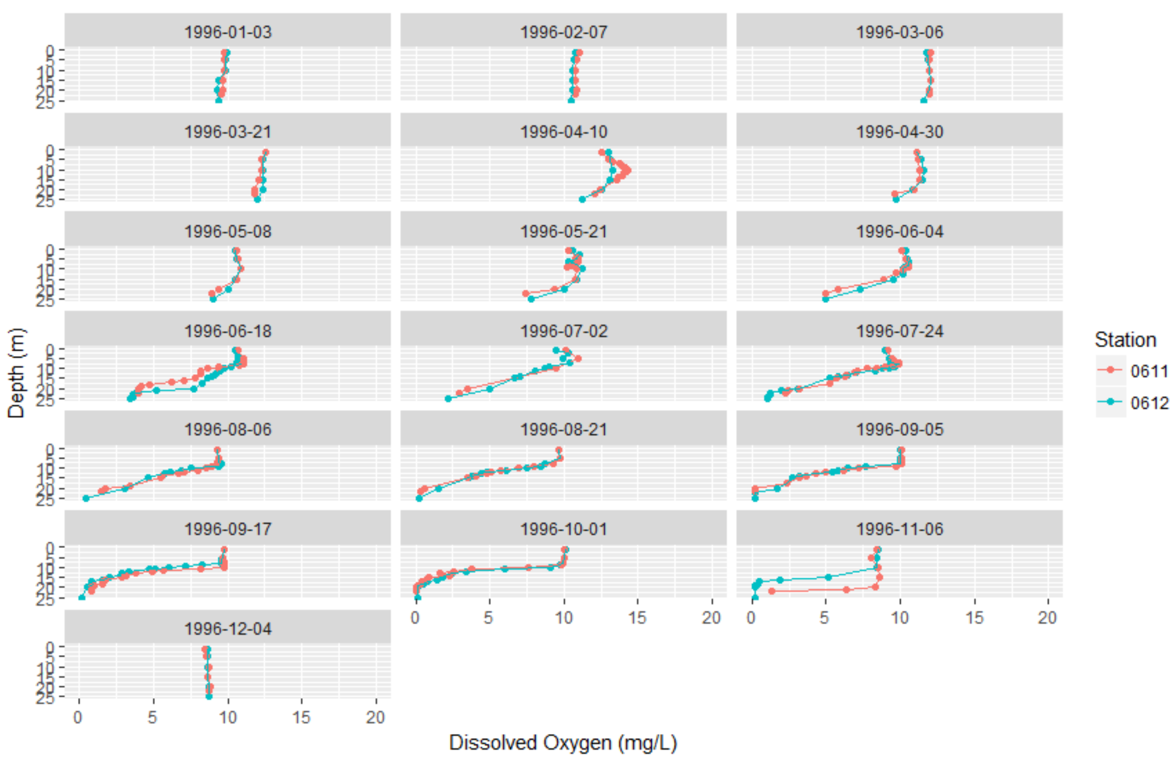

Figure A-10 Lake Sammamish dissolved oxygen profiles at stations 0611 and 0612 in 1996.

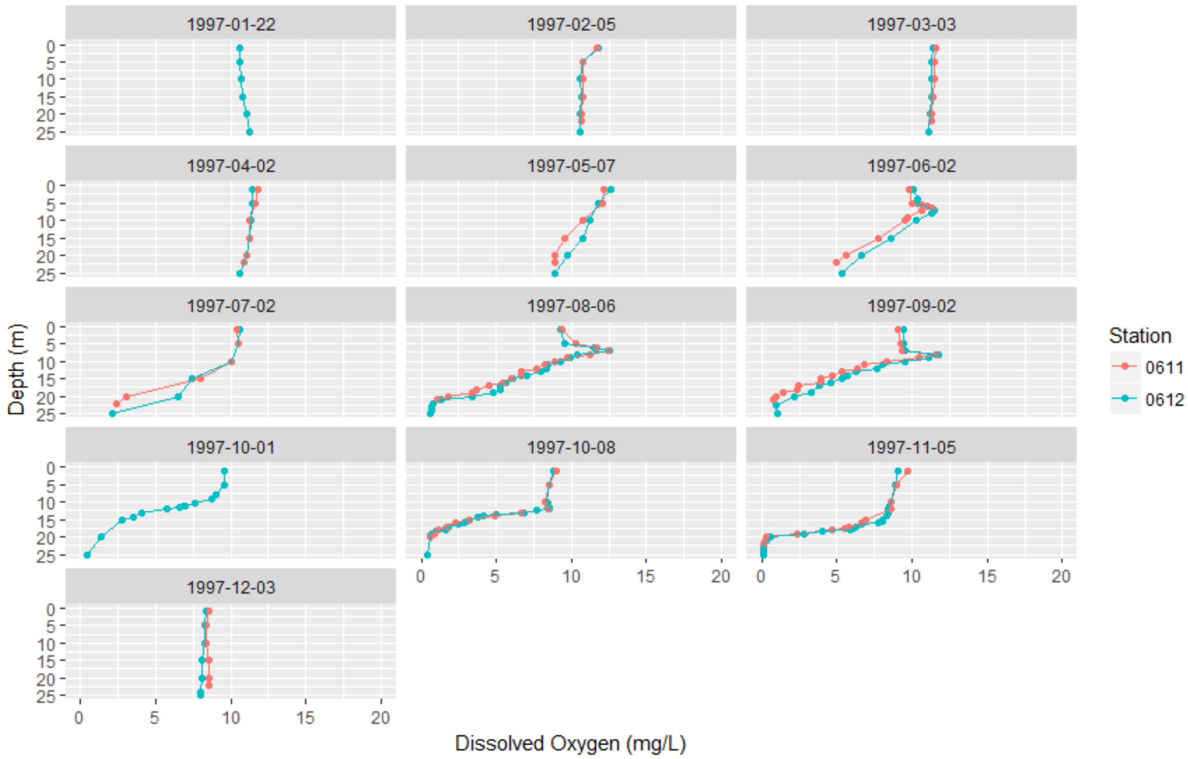

Figure A-11 Lake Sammamish dissolved oxygen profiles at stations 0611 and 0612 in 1997.

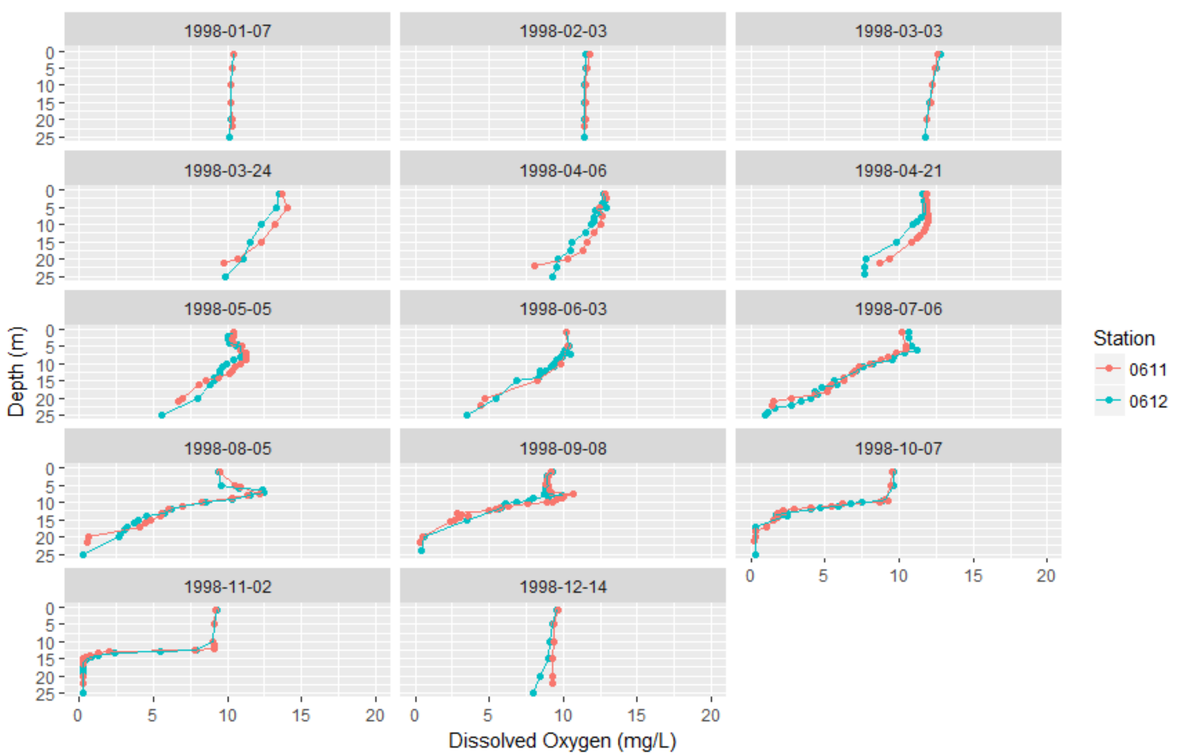

Figure A-12 Lake Sammamish dissolved oxygen profiles at stations 0611 and 0612 in 1998.

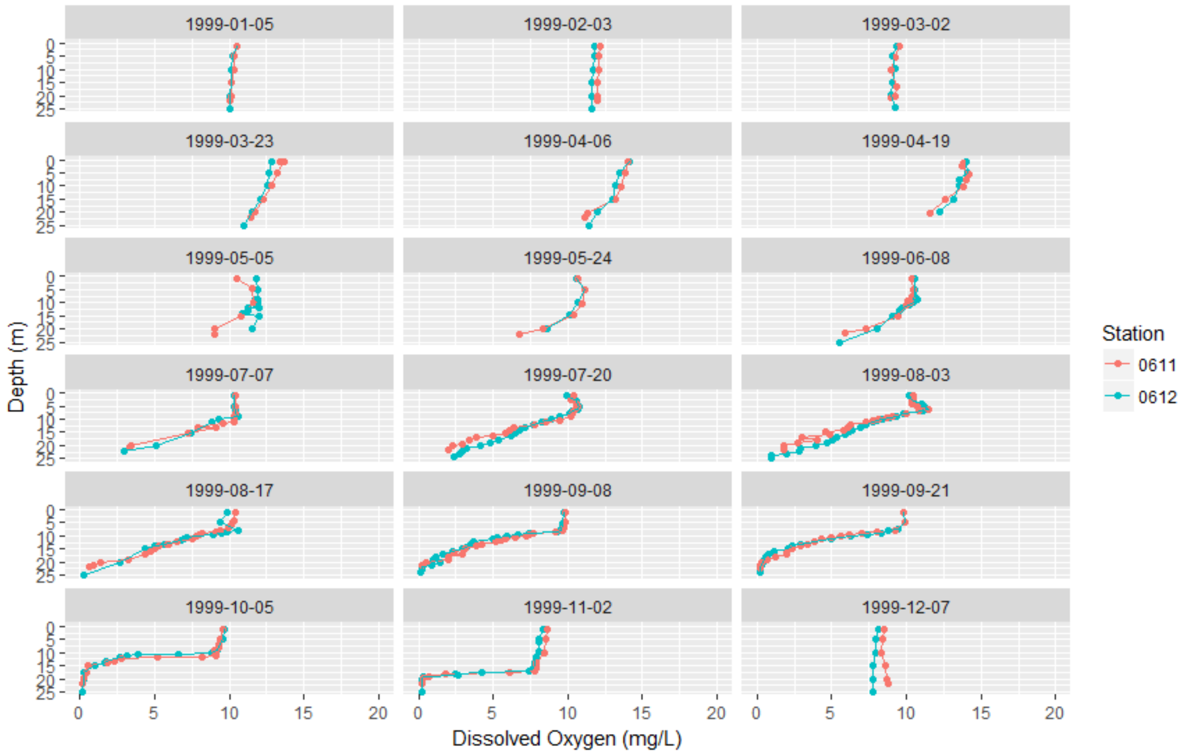

Figure A-13 Lake Sammamish dissolved oxygen profiles at stations 0611 and 0612 in 1999.

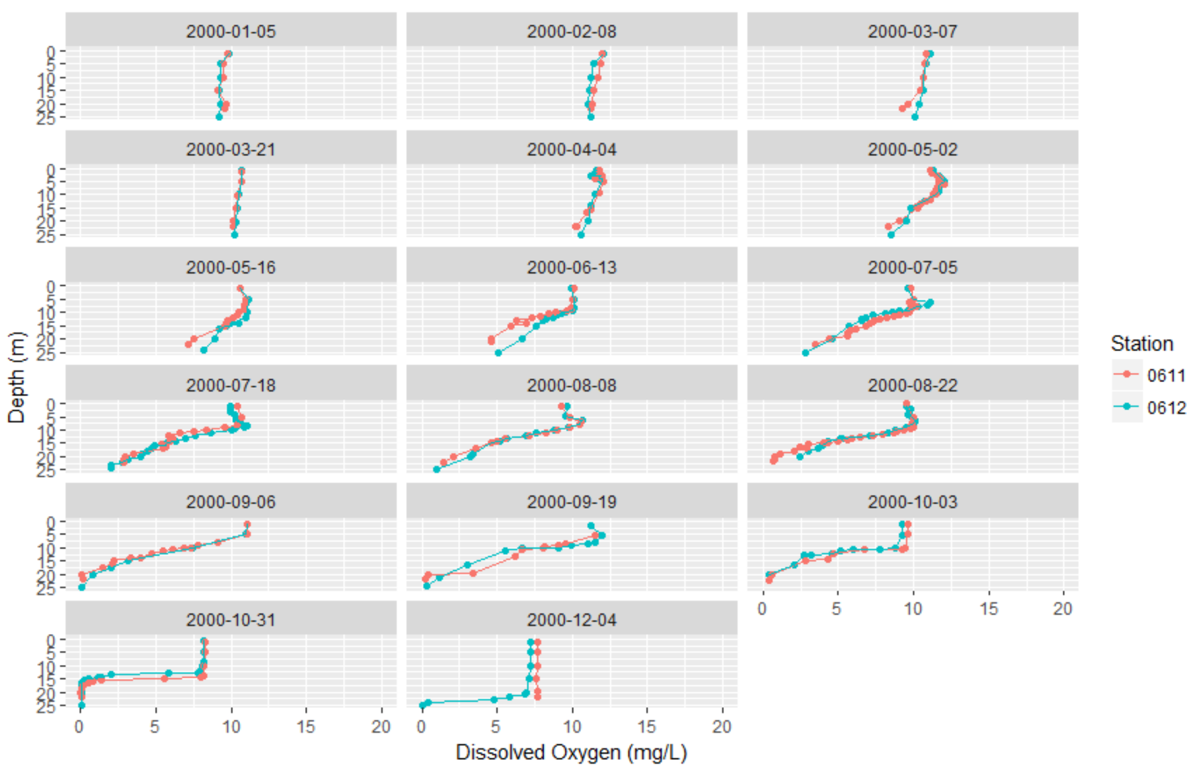

Figure A-14 Lake Sammamish dissolved oxygen profiles at stations 0611 and 0612 in 2000.

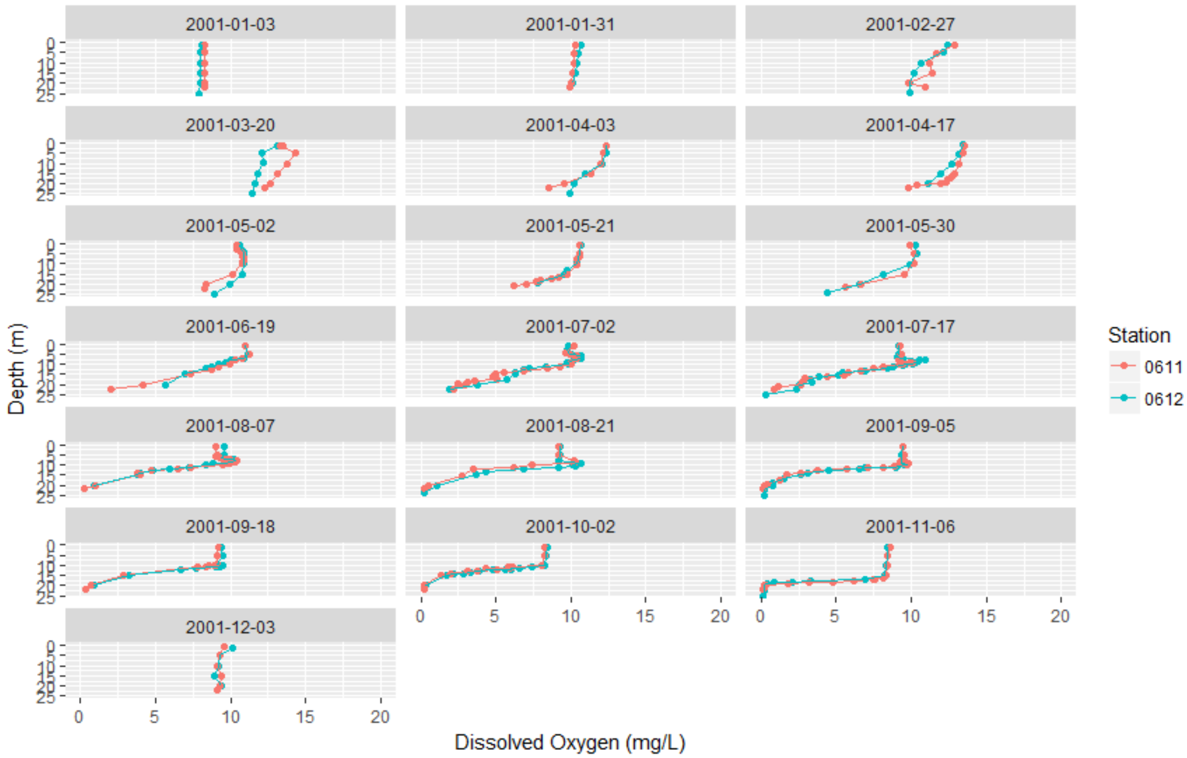

Figure A-15 Lake Sammamish dissolved oxygen profiles at stations 0611 and 0612 in 2001.

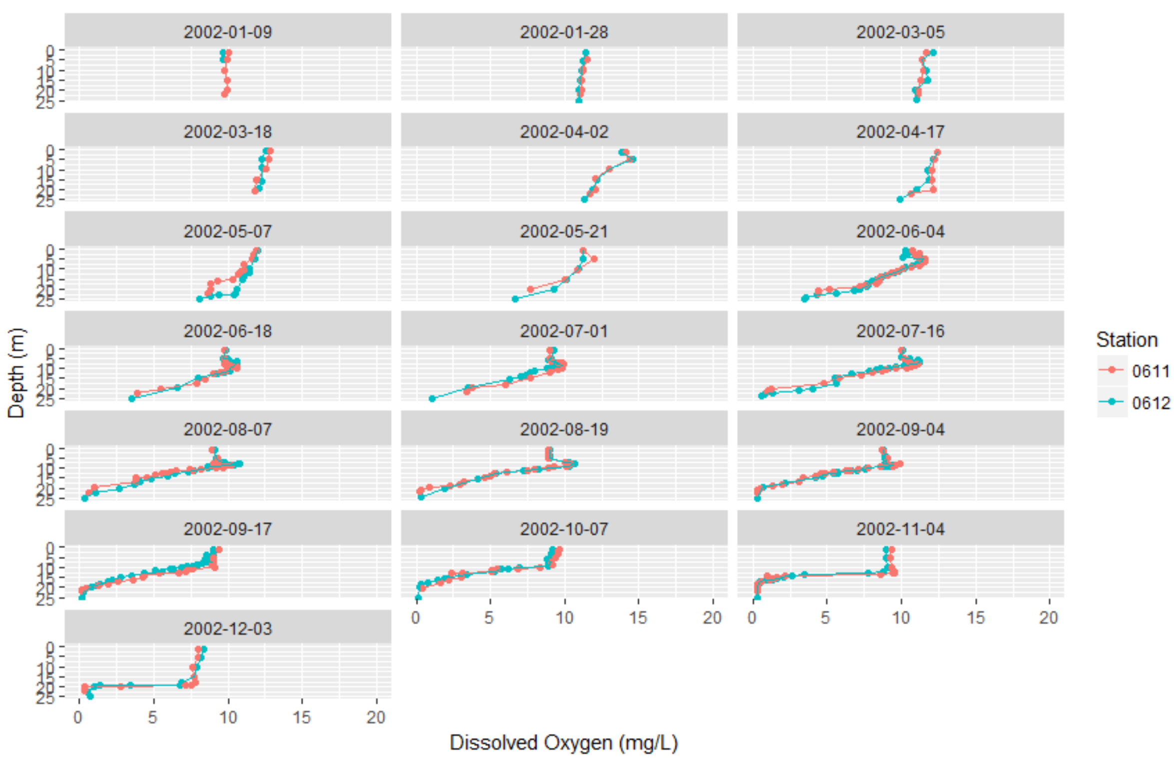

Figure A-16 Lake Sammamish dissolved oxygen profiles at stations 0611 and 0612 in 2002.

This page intentionally left blank

Appendix B: Station 0611 Mean August and September (1995–2002) Box Plots of Kokanee Habitats for the Baseline and 10 and 20 Cubic Feet per Second Withdrawal Scenarios

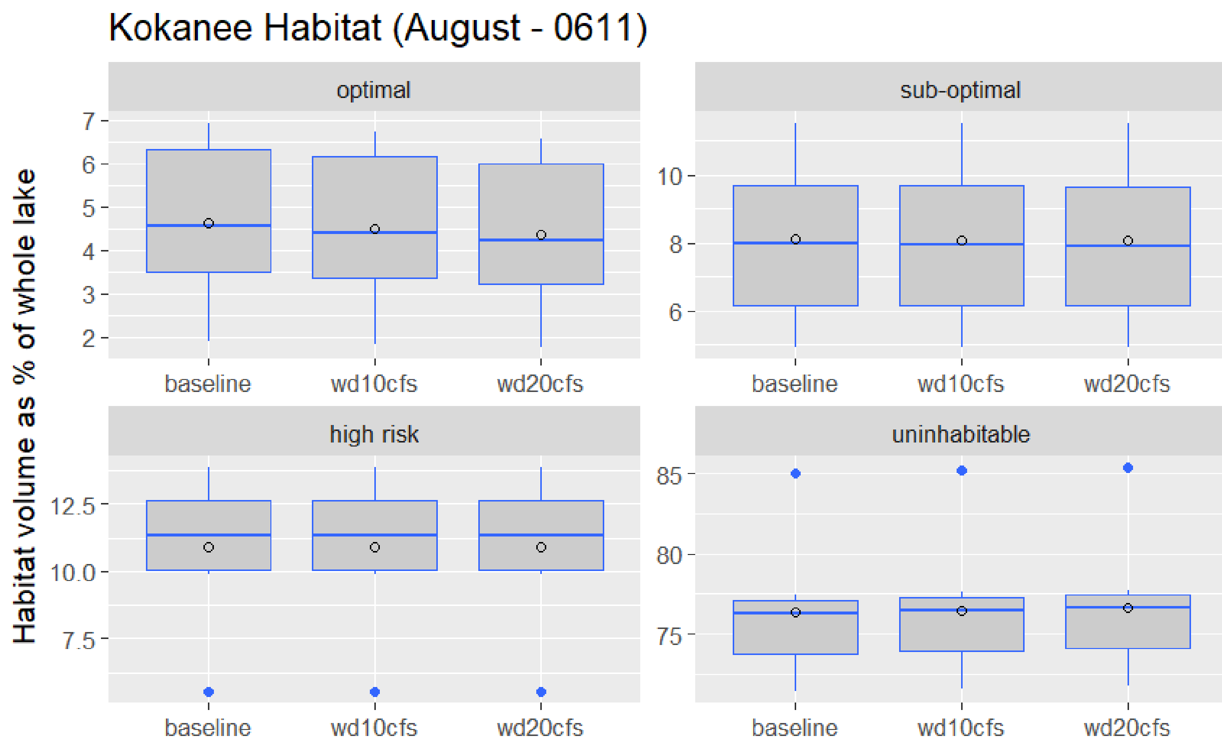

Figure B-1 Box plots of Station 0611 mean August (1995-2002) uninhabitable, high risk, sub-optimal, and optimal kokanee habitat volumes (shown as percent of total lake volume) for the baseline and 10 and 20 cfs withdrawal scenarios. Black circles within each box represent the mean habitat volume.

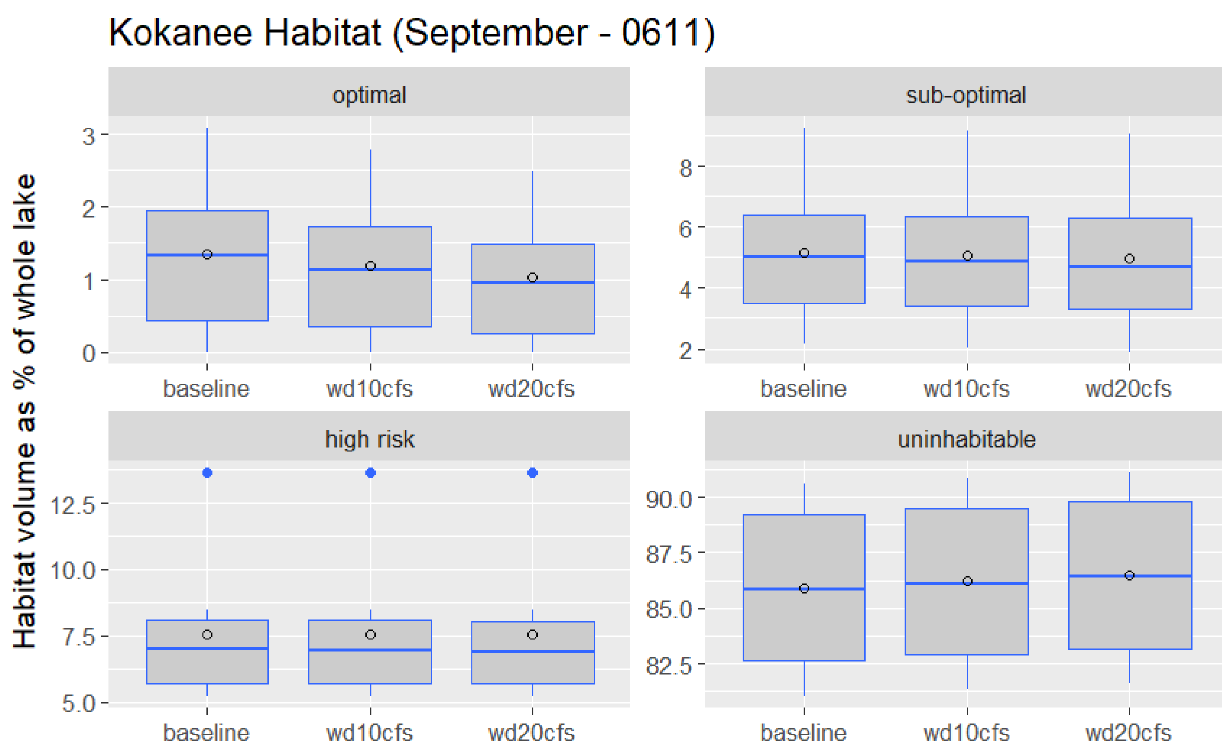

Figure B-2 Box plots of Station 0611 mean September (1995-2002) uninhabitable, high risk, sub-optimal, and optimal kokanee habitat volumes (shown as percent of total lake volume) for the baseline and 10 and 20 cfs withdrawal scenarios. Black circles within each box represent the mean habitat volume.