Appendix F – Lake Sammamish Nutrient and Stability Modeling, King County 2014

Estimating the Effects of a Hypothetical Hypolimnetic Withdrawal from Lake Sammamish on Sammamish River Nutrient Loading

January 2015

King County

Department of Natural Resources and Parks
Water and Land Resources Division
Science and Technical Support Section
King Street Center, KSC-NR-0600
201 South Jackson Street, Suite 600
Seattle, WA 98104
206-477-4800 TTY Relay: 711
www.kingcounty.gov/EnvironmentalScience

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DRAFT - Estimating the Effects of a Hypothetical Hypolimnetic Withdrawal From Lake Sammamish on Sammamish River Nutrient Loading

Prepared for:

King County Flood District

Submitted by:

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

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

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EXECUTIVE SUMMARY

This report describes the results of an evaluation of the potential effect of summer replacement (July 15 to September 15) of a portion of Lake Sammamish outlet flow to the Sammamish River with cool hypolimnetic water from the lake. The focus of the evaluation is on potential changes in nutrient loading to the river due to potentially higher (or lower) hypolimnetic nutrient concentrations relative to existing outlet concentrations during the proposed hypolimnetic withdrawal pumping period. Two hypolimnetic withdrawal scenarios are evaluated:

- **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.

The evaluation was based on a comparison to Sammamish River nutrient loading estimated as part of the development of a water quality model of the Sammamish. Comparisons were based on the results for the period 1995-2002 and analyses of lake nutrient profiling data collected over the same period that were conducted for this report.

Loading of dissolved phosphorus (the most biologically available form of this nutrient) is estimated to decrease rather than increase as a result of replacing a portion of Lake Sammamish surface outlet flow to the Sammamish River with cool hypolimnetic water. Total phosphorus loading is also estimated to decrease slightly.

Total nitrogen loading is estimated to increase from 10 to 20 percent and dissolved inorganic nitrogen loading is estimated to increase from 60 to 120 percent depending on the magnitude of the hypolimnetic withdrawal (10 or 20 cfs).

In general, existing inter-annual variability in nutrient loading from the lake to the Sammamish River appears to be larger than the magnitude of estimate changes (increasing or decreasing) resulting from the hypolimnetic withdrawal scenarios.

Determining the potential effect of an increase in nitrogen loading on the aquatic condition of the Sammamish River is beyond the scope of the work conducted for this report, but in general, freshwater systems in this region are generally considered to be phosphorus limited. Changes in soluble forms of nutrients would be expected to have the greatest impact on aquatic productivity.

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1.0. INTRODUCTION

Listing of Puget Sound Chinook under the federal Endangered Species Act (ESA) has triggered an intensive effort to identify causes of salmon population declines and measures that can be taken to maintain or improve existing conditions. The King County Flood Control District is investigating options to improve summer temperature conditions in the upper Sammamish River that would potentially benefit adult Chinook migrating through the river to spawn in the Big Bear Creek basin, tributaries to Lake Sammamish (including Issaquah Creek) or return to the hatchery on Issaquah Creek.

Summer temperature conditions in the upper Sammamish River consistently exceed the applicable state standard of 16 ^{o}C[1] as well as temperature thresholds considered to be potentially lethal to salmonids (e.g, 21 ^{o}C). Extremely high river temperatures in 1998 were believed to have contributed to Chinook pre-spawn mortality observed in the river that year (Fresh et al. 1999, Martz et al. 1999). It has also been suggested that the generally higher pre-spawn mortality rate of Chinook observed in Bear and Issaquah creeks relative to pre-spawn mortality in the Cedar River between 2002 and 2005 may be due in part to the relatively high temperatures experienced by fish migrating through the river (Berge et al. 2006). Fresh et al. (1999) suggested that the upper reach of the Sammamish River (perhaps exacerbated by high temperatures in the Ship Canal) represented a significant impediment to the passage of adult Chinook destined to spawn in the Issaquah Creek basin affecting the long-term viability of the population.

This report describes the results of an evaluation of the potential effect of summer replacement (July 15 to September 15) of a portion of Lake Sammamish outlet flow to the Sammamish River with cool hypolimnetic water from the lake. The focus of the evaluation is on potential changes in nutrient loading to the river due to potentially higher (or lower) hypolimnetic nutrient concentrations relative to existing outlet concentrations during the proposed hypolimnetic withdrawal pumping period. Two hypolimnetic withdrawal scenarios are evaluated:

- **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.

The evaluation was based on a comparison to Sammamish River nutrient loading estimated as part of the development of a water quality model of the Sammamish River (King County 2009). Comparisons were based on the results for the period 1995-2002 and analyses of

[1] The Sammamish River is designated as core summer salmonid habitat with a standard of 16 ^{o}C based on the 7-day moving average of the daily maximum temperature (Chapter 173-201A of the Washington Administrative Code).

lake nutrient profiling data collected over the same period that were conducted for this report.

1.1 Background

Welch et al. (1980) report that Lake Sammamish has a surface area of 19.8 km^2, holds approximately 3.5 x 108 m^3 of water, and has a mean residence time of 1.8 yr. The lake has a maximum depth of about 32 m and a mean depth of 17.7 m (Welch et al. 1980). The lake is an elongated fiord-like trough about 13 km long oriented along a north-south axis reflecting its glacial provenance. The lake typically stratifies thermally beginning in April and de-stratifies in November. As the lake stratifies, the hypolimnion becomes progressively depleted of oxygen resulting in anaerobic bottom waters in late summer. As hypolimnetic oxygen levels decline, nitrogen and phosphorus concentrations generally increase as a result of a combination of particulates settling from the epilimnion, nutrient release from anoxic bottom sediments and a slight excess of inflow over outflow (Birch and Spyridakis 1981).

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

Based on studies conducted by Isaac et al. (1966) on Lake Sammamish and similar studies related to an effort to divert secondary effluent from nearby Lake Washington (Edmondson 1968, 1969), wastewater from the Issaquah WWTP and the milk processing plant were completely diverted from Lake Sammamish by 1968. Lake Washington quickly recovered (Edmondson 1994), while the recovery of Lake Sammamish did not progress as quickly as expected based on flushing alone (Welch et al. 1975, Welch 1977). The delayed recovery of Lake Sammamish is well documented and has been attributed to a delayed reduction in sediment phosphorus release rates and the relatively smaller proportion of the total phosphorus load that was diverted (Birch et al. 1980; Welch et al., 1980; Welch 1985; Welch et al. 1986).

1.2 Objectives

The overall objective of the work described in this report was to use nutrient loading estimates calculated as part of the development of a 2-D Sammamish River water quality model (King County 2009) to evaluate the effect of two temperature management alternatives currently under consideration as part of the King County Flood District's Willowmoor Floodplain Restoration Project.

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Specific tasks to meet these objectives were:

- Interpolate nutrient (phosphorus and nitrogen) concentration time series from specific depths in Lake Sammamish near the proposed withdrawal location (Station 0611) based on routine nutrient profiling data collected by King County.
- Calculate potential loading changes resulting from replacing 10 or 20 cfs of surface outlet flow with hypolimnetic water.
- Summarize results in tabular and graphical format and include an assessment of the effects of the hypothetical withdrawal on river nutrient loading during the period July 15 to September 15.

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2.0. METHODS

A Matlab script was developed to interpolate each nutrient profile collected at Station 0611 (see Figure 1) at 1 m intervals and these uniform profiles were then interpolated to a daily time frequency for the period 1995 to 2002. Station 0611 is the station closest to the proposed hypolimnetic withdrawal location.

The nutrient time series for the 15 m depth was used in combination with daily outlet and withdrawal flow values (and interpolated weir outlet concentrations) to estimate how nutrient loading would potentially change in response to replacing a portion of the weir outlet flow with hypolimnetic water between July 15 and September 15 each year.

Loading estimates under existing conditions for each nutrient were then summarized for each year for the July 15 to September 15 period and compared to the existing (or baseline) estimates for the same years and period. The nutrient concentration time series were also averaged across years for each day between July 15 to September 15 for the outlet concentration and the concentrations observed at 10, 15 and 25 m at Station 0611 to illustrate why loading of a particular nutrient was expected to increase or decrease. The relative change in nutrient loading was also compared to estimated loading from Big Bear Creek for the same time period to give some context for expected magnitude of effect of the estimated change (either up or down).

The nutrients that were evaluated included:

- Total Phosphorus (TP)
- Soluble Reactive Phosphorus (SRP) [2]
- Total Nitrogen (TN)
- Nitrate+Nitrite Nitrogen (NO3-N)
- Ammonia Nitrogen (NH3-N)

Because the original Sammamish River nutrient loading estimates for NO3-N and NH3-N were presented as the dissolved inorganic nitrogen (i.e., the sum of the two soluble nitrogen compounds) (King County 2009), these two compounds were also summed for comparison in this report.

[2] The King County laboratory reports Soluble Reactive Phosphorus using the term Orthophosphate Phosphorus.

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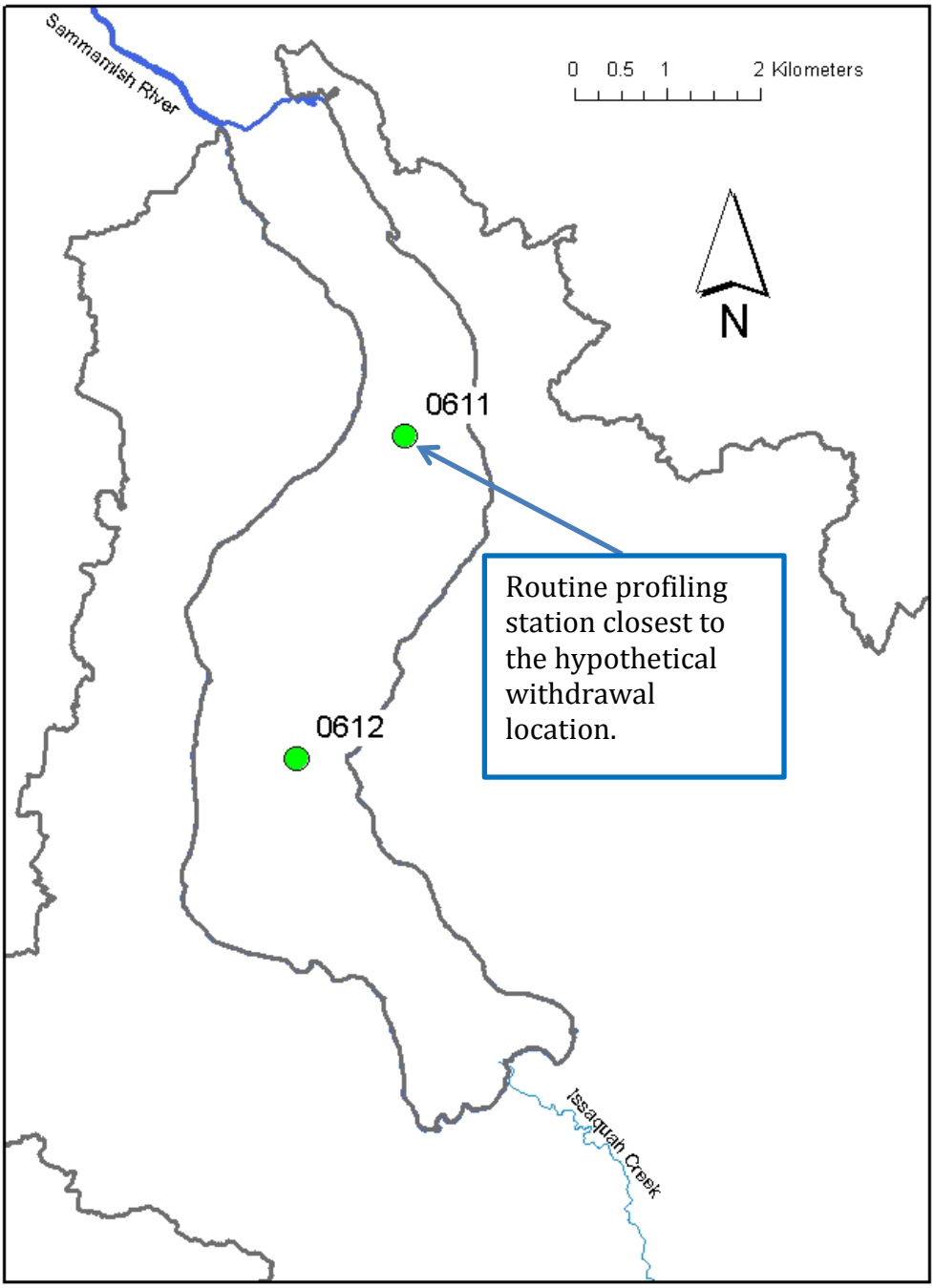

Figure 1. Map showing Lake Sammamish and locations of central routine water quality profiling stations 0611 and 0612. Major inflow (Issaquah Creek) and the lake outflow (Sammamish River) also shown.

3.0. RESULTS

In general, phosphorus (TP and SRP) loading was slightly lower on average under the hypothetical withdrawal conditions relative to the 1995-2002 existing conditions (Table 1). In comparison to existing loading, a 4 and 9 percent reduction is estimated for TP and SRP loading, respectively, under the 20 cfs withdrawal scenario. It should also be noted that the estimated magnitude of change in phosphorus loading appears to be much smaller than the inter-annual variability in existing loading conditions at the weir.

Although TP and SRP concentrations do increase between July 15 and September 15 in the deeper portion of the hypolimnion (e.g., 20 m depth), concentrations at 15 m remain below or very near the concentrations observed at the lake outlet during this time period (see Figures 2 and 3).

Larger changes are estimated for nitrogen loading, with an estimated increase in TN and DIN loading (Table 1). TN loading is estimated to increase between 10 and 21 percent and DIN loading is estimated to increase between 60 and 120 percent depending on the scenario. It should also be noted that the estimated magnitude of change in nitrogen loading, although rather large, appears to be much smaller than the inter-annual variability in existing loading conditions at the weir.

TN loading is estimated to increase because TN concentrations between 10 and 20 m at Station 0611 are typically higher than concentrations observed at the lake outlet (see Figure 4). DIN loading is estimated to increase for the same reason; DIN concentrations between 10 and 20 m are all more than the DIN concentrations observed at the lake outlet between July 15 and September 15.

To put these potential increases and decreases in loading in some perspective, loading from all surface runoff sources to the Sammamish River for the period July 15 to September 15 for the period 1995-2002 calculated as part of the development of a Sammamish River water quality model (King County 2009) are compared to the hypolimnetic withdrawal scenario loading estimates in Table 2. The first observation that can be made upon reviewing Table 2 is that nutrient loading to the Sammamish River during summer is dominated by loading from Lake Sammamish due to the generally lower flow and nutrient concentrations in tributaries during this time period.

Comparison of changes in phosphorus loading (between 0.03 and 0.10 kg day^{-1}) indicate that the magnitude of estimated decreases in loading are of smaller in magnitude to estimated loading from Big Bear Creek and similar in magnitude to loading from Little Bear and Swamp Creek (Table 2). The increase in TN loading (between about 5 and 10 kg day^{-1}) is generally larger than the estimated loading from any of the four major tributaries to the river (Table 2). The increase in DIN loading (between 7.3 and 14.6 kg day^{-1}) is generally about an order of magnitude higher than the average estimated loading from river tributaries (Table 2).

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Table 1. Daily average nutrient loads (July 15-September 15) to the Sammamish River from Lake Sammamish for 1995-2002 for existing conditions and the 10 and 20 cfs hypolimnetic withdrawal scenarios.

Scenario	year	TP	SRP	TN	DIN
			kg day^{-1}		
Weir outlet	1995	2.27	0.19	27.2	6.0
Weir outlet	1996	2.47	0.57	56.6	16.8
Weir outlet	1997	4.84	2.65	103.2	32.7
Weir outlet	1998	1.86	0.23	29.3	6.2
Weir outlet	1999	2.89	0.31	63.9	17.3
Weir outlet	2000	1.55	0.20	28.7	7.5
Weir outlet	2001	2.92	0.31	36.3	4.8
Weir outlet	2002	2.21	0.29	29.0	4.1
	Avg ± 1 SD	2.63 ± 1.01	0.59 ± 0.84	46.8 ± 26.8	11.9 ± 9.9
wd10cfs	1995	2.04	0.16	34.8	13.8
wd10cfs	1996	2.41	0.57	58.6	24.0
wd10cfs	1997	4.63	2.55	108.8	41.9
wd10cfs	1998	1.52	0.20	34.7	13.8
wd10cfs	1999	3.61	0.34	67.4	23.9
wd10cfs	2000	1.45	0.17	36.4	16.6
wd10cfs	2001	2.85	0.28	37.9	8.5
wd10cfs	2002	2.13	0.27	34.1	11.0
	Avg ± 1 SD	2.58 ± 1.09	0.57 ± 0.81	51.6 ± 26.4	19.2 ± 10.8
wd20cfs	1995	1.82	0.13	42.5	21.7
wd20cfs	1996	2.34	0.58	60.6	31.1
wd20cfs	1997	4.41	2.45	114.4	51.2
wd20cfs	1998	1.18	0.17	40.0	21.5
wd20cfs	1999	4.33	0.37	70.9	30.5
wd20cfs	2000	1.34	0.14	44.0	25.8
wd20cfs	2001	2.77	0.26	39.6	12.1
wd20cfs	2002	2.05	0.25	39.2	18.0
	Avg ± 1 SD	2.53 ± 1.25	0.54 ± 0.78	56.4 ± 26.1	26.5 ± 11.8

TP = Total Phosphorus, SRP = Soluble Reactive Phosphorus, TN = Total Nitrogen, DIN = Dissolved Inorganic Nitrogen (sum of nitrate+nitrate and ammonia nitrogen)

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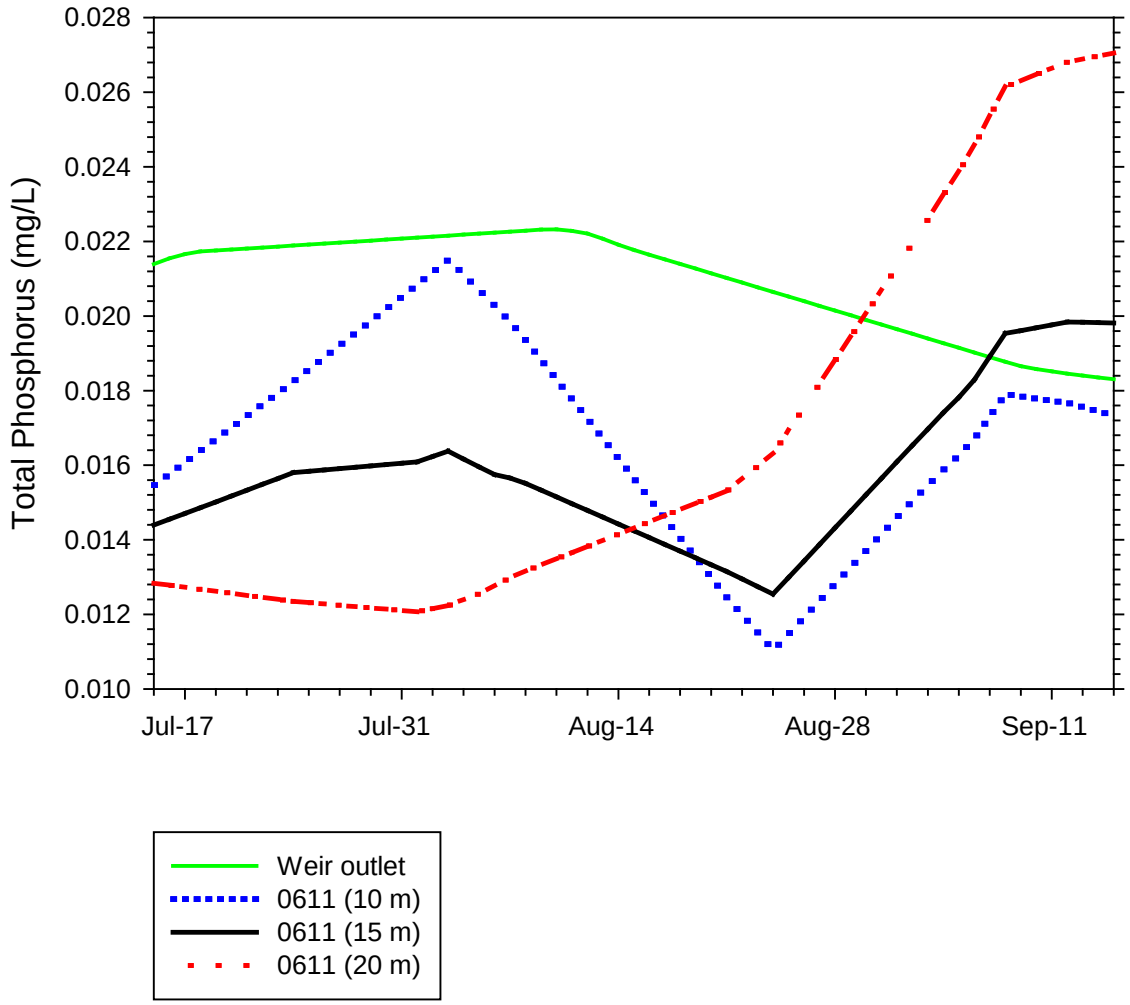

Figure 2. Daily average total phosphorus (TP) concentrations at the weir outlet and at Station 0611 (10, 15 and 20 m depths) based on the eight years of routine monitoring data (1995-2002) collected at these two locations.

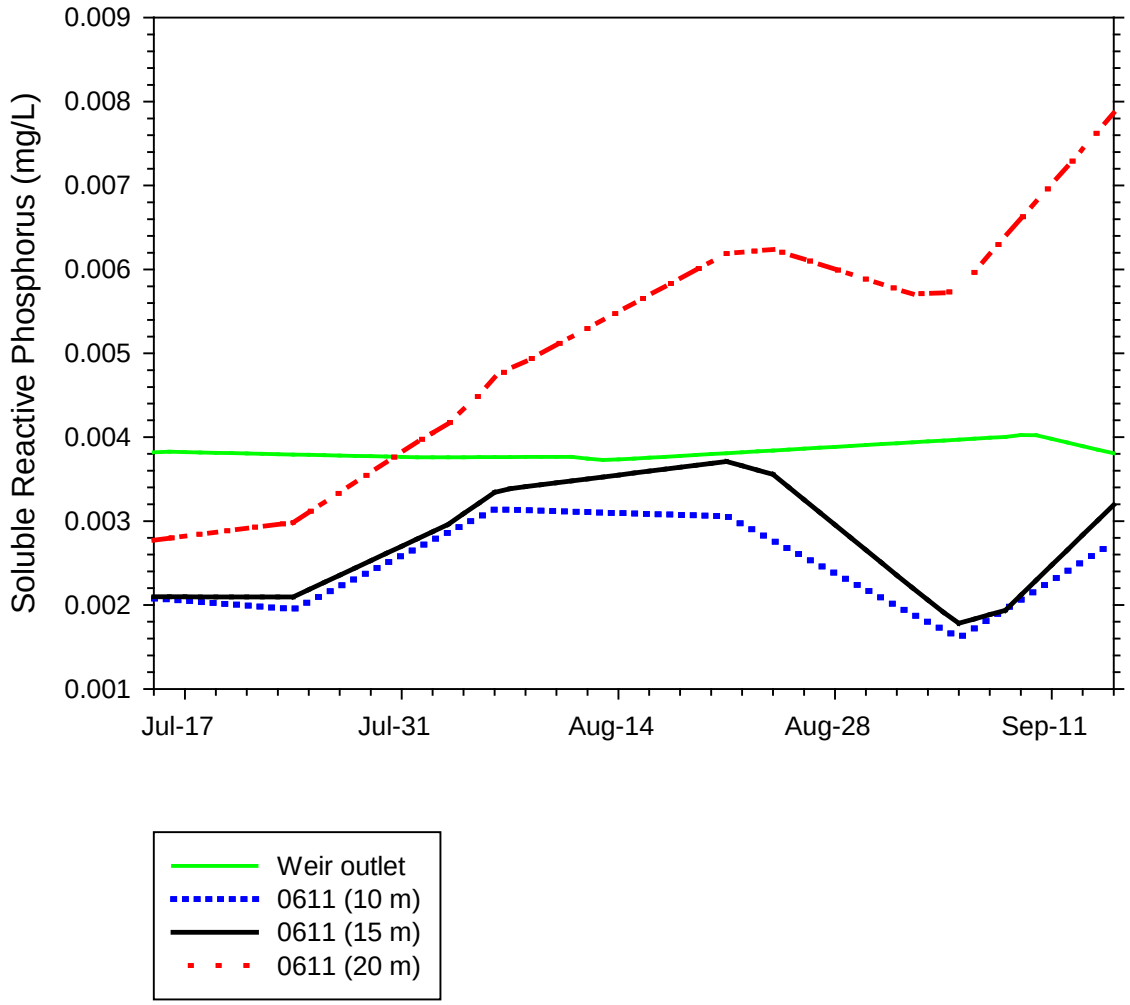

Figure 3. Daily average Soluble Reactive Phosphorus (SRP) concentrations at the weir outlet and at Station 0611 (10, 15 and 20 m depths) based on the eight years of routine monitoring data (1995-2002) collected at these two locations.

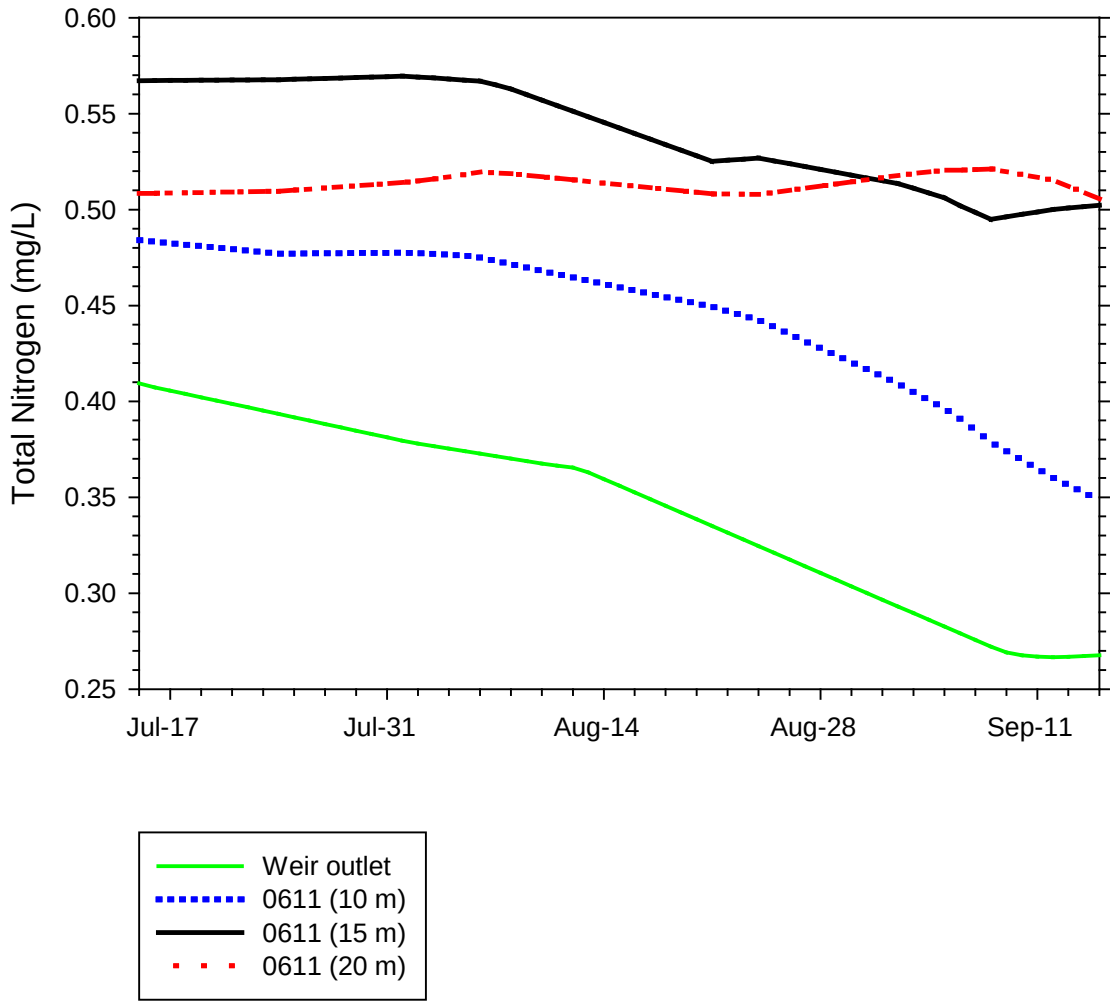

Figure 4. Daily average total nitrogen (TN) concentrations at the weir outlet and at Station 0611 (10, 15 and 20 m depths) based on the eight years of routine monitoring data (1995-2002) collected at these two locations.

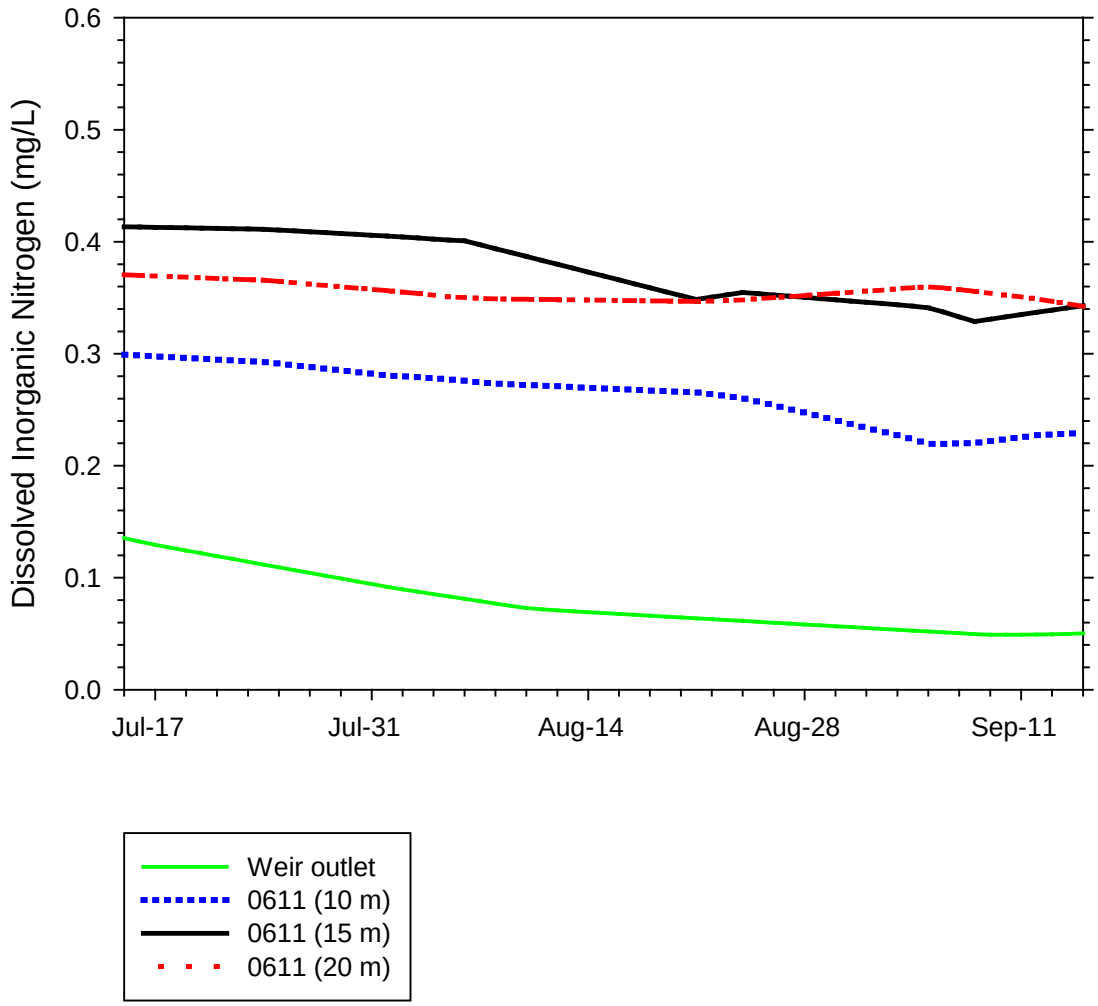

Figure 5. Daily average dissolved inorganic nitrogen (DIN) concentrations at the weir outlet and at Station 0611 (10, 15 and 20 m depths) based on the eight years of routine monitoring data (1995-2002) collected at these two locations.

Table 2. Average daily nutrient loads to the Sammamish River from all sources for the period July 15-September 15 (1995-2002) for existing conditions. Estimated loading for the two hypolimnetic withdrawal scenarios are provided for comparison.

Scenario	TP	SRP	TN	DIN
		kg day^{-1}		
Big Bear	0.17	0.07	1.8	1.0
Distributed	0.06	0.03	0.8	0.6
Little Bear	0.09	0.04	1.0	0.8
North	0.20	0.10	2.3	1.7
Swamp	0.07	0.03	0.9	0.6
Weir	2.63	0.59	46.8	11.9
wd10cfs	2.58	0.57	51.6	19.2
Δ (wd10cfs – Weir)	-0.05	-0.03	4.8	7.3
wd20cfs	2.53	0.54	56.4	26.5
Δ (wd20cfs – Weir)	-0.10	-0.05	9.6	14.6

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4.0. CONCLUSIONS

Loading of dissolved phosphorus (the most biologically available form of this nutrient) is estimated to decrease rather than increase as a result of replacing a portion of Lake Sammamish surface outlet flow to the Sammamish River with cool hypolimnetic water during the period of July 15 to September 15. Total phosphorus loading is also estimated to decrease slightly.

Total nitrogen loading is estimated to increase from 10 to 20 percent and dissolved inorganic nitrogen loading is estimated to increase from 60 to 120 percent depending on the magnitude of the hypolimnetic withdrawal (10 or 20 cfs).

In general, existing inter-annual variability in nutrient loading from the lake to the Sammamish River appears to be larger than the magnitude of estimate changes (increasing or decreasing) resulting from the hypolimnetic withdrawal scenarios.

Determining the potential effect of an increase in nitrogen loading on the aquatic condition of the Sammamish River is beyond the scope of the work conducted for this report, but in general, freshwater systems in this region are generally considered to be phosphorus limited. Changes in soluble forms of nutrients would be expected to have the greatest impact on aquatic productivity.

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5.0. REFERENCES

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

September 2014

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Department of Natural Resources and Parks
Water and Land Resources Division
Science and Technical Support Section
King Street Center, KSC-NR-0600
201 South Jackson Street, Suite 600
Seattle, WA 98104
206-477-4800 TTY Relay: 711
www.kingcounty.gov/EnvironmentalScience

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

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Figures

Figure 1. 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) also shown. The segment where the hypothetical hypolimnetic withdrawal was placed is shaded gray. 4

Figure 2. Monthly averaged thermocline depths based on the eight years of output from the 2-D CE-QUAL-W2 Lake Sammamish model. 6

Figure 3. Monthly averaged Schmidt stability based on the eight years of output from the 2-D CE-QUAL-W2 Lake Sammamish model. 7

Figure 4. 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. 8

Figure 5. Monthly averaged 17 °C isotherms based on the eight years of output from the 2-D CE-QUAL-W2 Lake Sammamish model. 9

Figure 6. Monthly averaged favorable salmonid habitat volume based on eight years of ouput from the 2-D CE-QUAL-W2 Lake Sammamish model (volume <17 °C and greater than 4 mg DO per liter) isotherms based on the eight years of output from the 2-D CE-QUAL-W2 Lake Sammamish model. 11

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Table 1. Average monthly (May-October) favorable salmonid habitat volumes (shown as percent of total lake volume) predicted by the 2-D CE-QUAL-W2 Lake Sammamish model for each of the three temperature thresholds. 10

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EXECUTIVE SUMMARY

This report describes the results of the application of an existing 2-dimensional (vertical and longitudinally) lake temperature model developed for Lake Sammamish to evaluate the effect of two Sammamish River temperature management scenarios on the thermal structure of Lake Sammamish:

- **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.

In addition to modeling these two management alternatives, 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.

Based on the modeling results, withdrawal of up to 20 cfs of water from the 15 m depth in Lake Sammamish between mid-July to mid-September (conceptually replacing the equivalent amount of lake outlet flow) does not appear to have a significant effect on lake thermal structure or significantly impact favorable lake habitat for kokanee. This is likely due to selective withdrawal of colder water below the thermocline as relatively strong lake thermal stratification is established by July with the seasonal thermocline established at a depth less than 15 meters until late September or October when the lake begins to cool and the thermocline begins to extend to the 15 meter depth or deeper.

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1.0. INTRODUCTION

Listing of Puget Sound Chinook under the federal Endangered Species Act (ESA) has triggered an intensive effort to identify causes of salmon population declines and measures that can be taken to maintain or improve existing conditions. The King County Flood Control District is investigating options to improve summer temperature conditions in the upper Sammamish River that would potentially benefit adult Chinook migrating through the river to spawn in the Big Bear Creek basin, tributaries to Lake Sammamish (including Issaquah Creek) or return to the hatchery on Issaquah Creek.

Summer temperature conditions in the upper Sammamish River consistently exceed the applicable state standard of 16 ^{o}C[1] as well as temperature thresholds considered to be potentially lethal to salmonids (e.g, 21 ^{o}C). Extremely high river temperatures in 1998 were believed to have contributed to Chinook pre-spawn mortality observed in the river that year (Fresh et al. 1999, Martz et al. 1999). It has also been suggested that the generally higher pre-spawn mortality rate of Chinook observed in Bear and Issaquah creeks relative to pre-spawn mortality in the Cedar River between 2002 and 2005 may be due in part to the relatively high temperatures experienced by fish migrating through the river (Berge et al. 2006). Fresh et al. (1999) suggested that the upper reach of the Sammamish River (perhaps exacerbated by high temperatures in the Ship Canal) represented a significant impediment to the passage of adult Chinook destined to spawn in the Issaquah Creek basin affecting the long-term viability of the population.

This report describes the results of the application of an existing lake temperature model developed for Lake Sammamish to evaluate the effect of two Sammamish River temperature management scenarios on the thermal structure of Lake Sammamish:

- **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.

In addition to modeling these two management alternatives, 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.

A worst-case scenario was also conducted in which the surface outlet from the lake to the Sammamish River was replaced with an equivalent year-round hypolimnetic withdrawal.

[1] The Sammamish River is designated as core summer salmonid habitat with a standard of 16 ^{o}C based on the 7-day moving average of the daily maximum temperature (Chapter 173-201A of the Washington Administrative Code).

1.1 Background

As part of King County's Sammamish-Washington Analysis and Modeling Program (SWAMP), a 3-D hydrodynamic model of Lake Sammamish was developed (King County 2008) along with a suite of other models, including HSPF watershed models of the Sammamish basin (King County 2003) and a laterally-averaged 2-D model of the Sammamish River (King County 2009); the outlet of Lake Sammamish. In addition to the 3-D model of Lake Sammamish, a laterally-averaged 2-D model of the lake was also developed to troubleshoot the development of the 3-D model, which at that time had previously been applied to only one lake; nearby Lake Washington (Kim et al. 2006; Cerco et al. 2006).

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 developed 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) and CE-QUAL-W2 has been used in hundreds of lake and reservoir modeling studies (Cole and Wells 2006).[2]

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 primarily because of the more flexible features of the CE-QUAL-W2 model that readily allow the modeling of withdrawal scenarios.[3] Depending on the estimated effects on lake thermal structure based on the 2-D model, a more resource intensive investigation using a 3-D model could be undertaken.

1.2 Objectives

The overall objective of the work described in this report was to use the existing 2-D Lake Sammamish temperature model to evaluate two temperature management alternatives currently under consideration as part of the King County Flood District's Willowmoor Floodplain Restoration Project.

Specific tasks to meet these objectives were:

- Revise input files as needed to create the two temperature management scenarios.
- Summarize results in tabular and graphical format and include an assessment of the effects of the hypothetical withdrawal on lake thermal structure.

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

[3] 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.

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2.0. METHODS

For information on the development and testing of the model, the reader is referred to King County (2013). In general, statistical comparisons of model output to observed temperatures indicated reasonably low bias and error. Mean bias was 0.16 ^{o}C and the root mean square error (RMSE) was 1.08 ^{o}C for the period 1995-2002 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 longitudinal resolution of the 2-D grid is illustrated in Figure 1. The lake is represented by 22 longitudinal segments and vertical resolution was defined using 0.91 m thick layers resulting in a close approximation of the 3-D model vertical layering scheme. The QUICKEST-ULTIMATE numerical transport solution scheme was used with the recommended time weighting factor (THETA) of 0.55. The vertical turbulence algorithm W2N was used with an implicit scheme and a maximum vertical eddy viscosity of 0.01 $m^2 s^{-1}$. The model time step was optimized and averaged about 100 seconds in each model run, which resulted in 8-year simulations (1995-2002) that took approximately 30 minutes to run on a 64-bit Windows PC equipped with two 2.66 GHz quad core processors. Model output was written to a self-describing binary file format (NetCDF) during runtime resulting in an 841 MB file for each 8-year model run.

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. A file was also developed that represented replacing the surface outlet flow with an equivalent year-round hypolimnetic withdrawal. 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 1).

2.1 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 to evaluate the potential effects of the hypothetical withdrawal scenarios on lake thermal structure and kokanee habitat. Details of those methods can be found in King County (2013). The methods are briefly described below.

2.1.1 Lake Analyzer

Model output from the central lake monitoring location (Station 0612) was processed and analyzed using Lake Analyzer (Read et al. 2011), a Matlab program designed for analyzing high resolution lake profiling data that is also well suited to analyzing lake temperature

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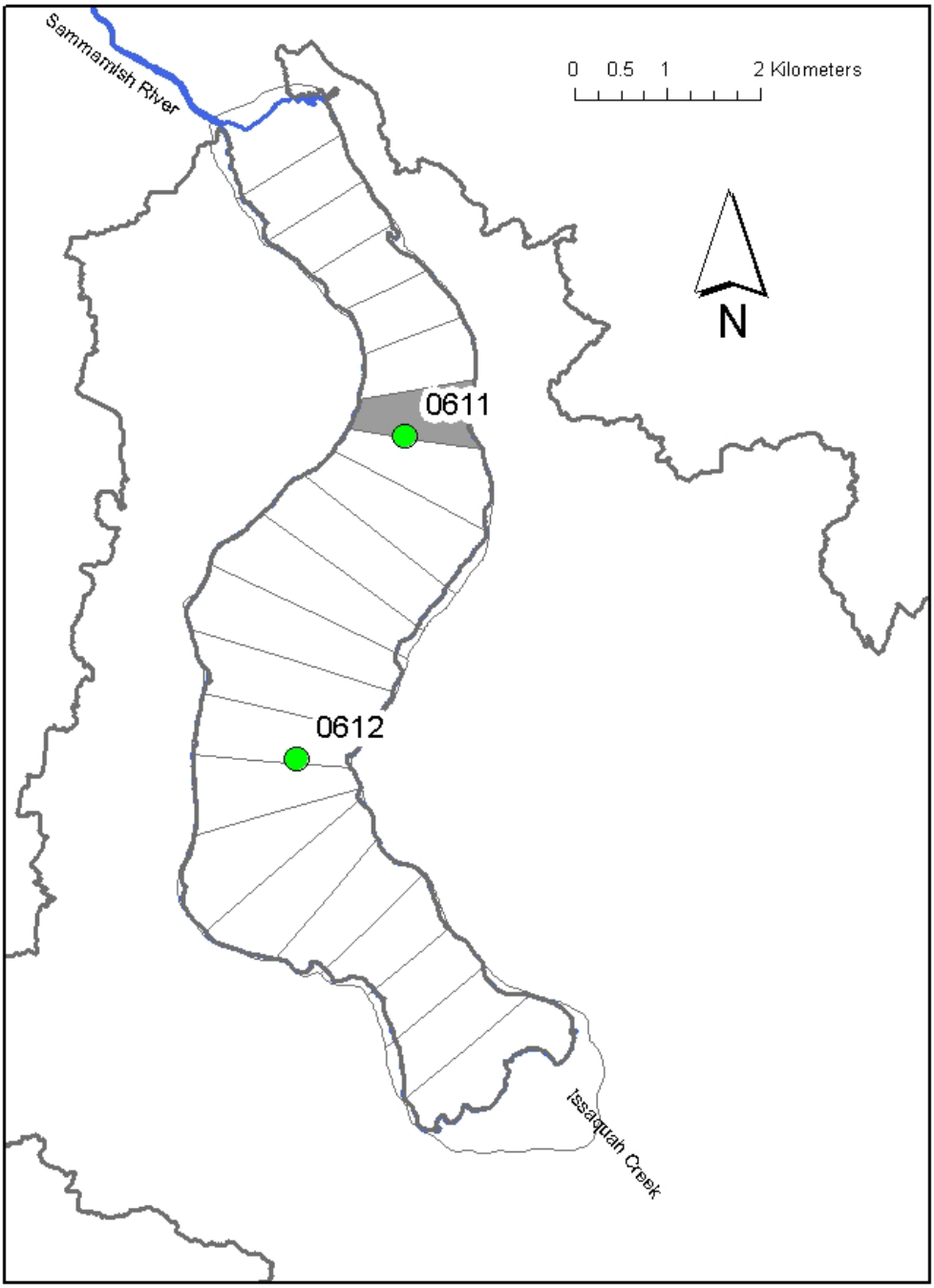

Figure 1. Map showing the longitudinal segmentation of the Lake Sammamish CE-QUAL-W2 grid and locations of routine water quality profiling stations. Major inflow (Issaquah Creek) and the lake outflow (Sammamish River) also shown. The segment where the hypothetical hypolimnetic withdrawal was placed is shaded gray.

model output. Lake Analyzer calculated 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). Lake Analyzer also produced color contour plots of temperature that visually illustrated changes in lake temperature under different management scenarios.

2.1.2 17 °C Isotherm

Model output for the grid cell representing Station 0612 was also processed using Matlab scripts that determined the isotherms for 17 °C, which was identified as a kokanee avoidance threshold (i.e., kokanee would avoid areas of the lake with a temperature greater than 17 °C) (Kirk Krueger, Washington Department of Fish and Wildlife, pers. comm., email, May 28, 2013).

2.1.3 Favorable Habitat Volume for Kokanee

An analysis of the observed DO data collected from the central long-term monitoring station (Station 0612) was conducted to estimate the daily volume of the lake with DO concentrations less than 4 mg/L. The daily volume of the lake for each model scenario and temperature threshold was subtracted from the volume of the lake with DO concentrations below 4 mg/L to provide an estimate of the daily habitat volume for each temperature threshold accounting for the DO squeeze. Following Berge (2009), the volume of the lake with temperatures below 17 °C (based on model output) and DO concentrations greater than 4 mg/L (based on observed data) were characterized as “favorable” salmonid habitat.

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3.0. RESULTS

3.1 Lake Analyzer

3.1.1 Thermocline Depth

There appeared to be no significant effect of a July 15-September 15 hypolimnetic withdrawal on thermocline depth. The monthly average thermocline depth (1995-2002) was essentially the same for the Baseline, 10 cfs, and 20 cfs withdrawal scenarios (Figure 2). Replacing the outlet withdrawal with a year-round hypolimnetic withdrawal did have an apparent effect on the thermocline depth (deepening), particularly from about the beginning of June through September (see Figure 2).

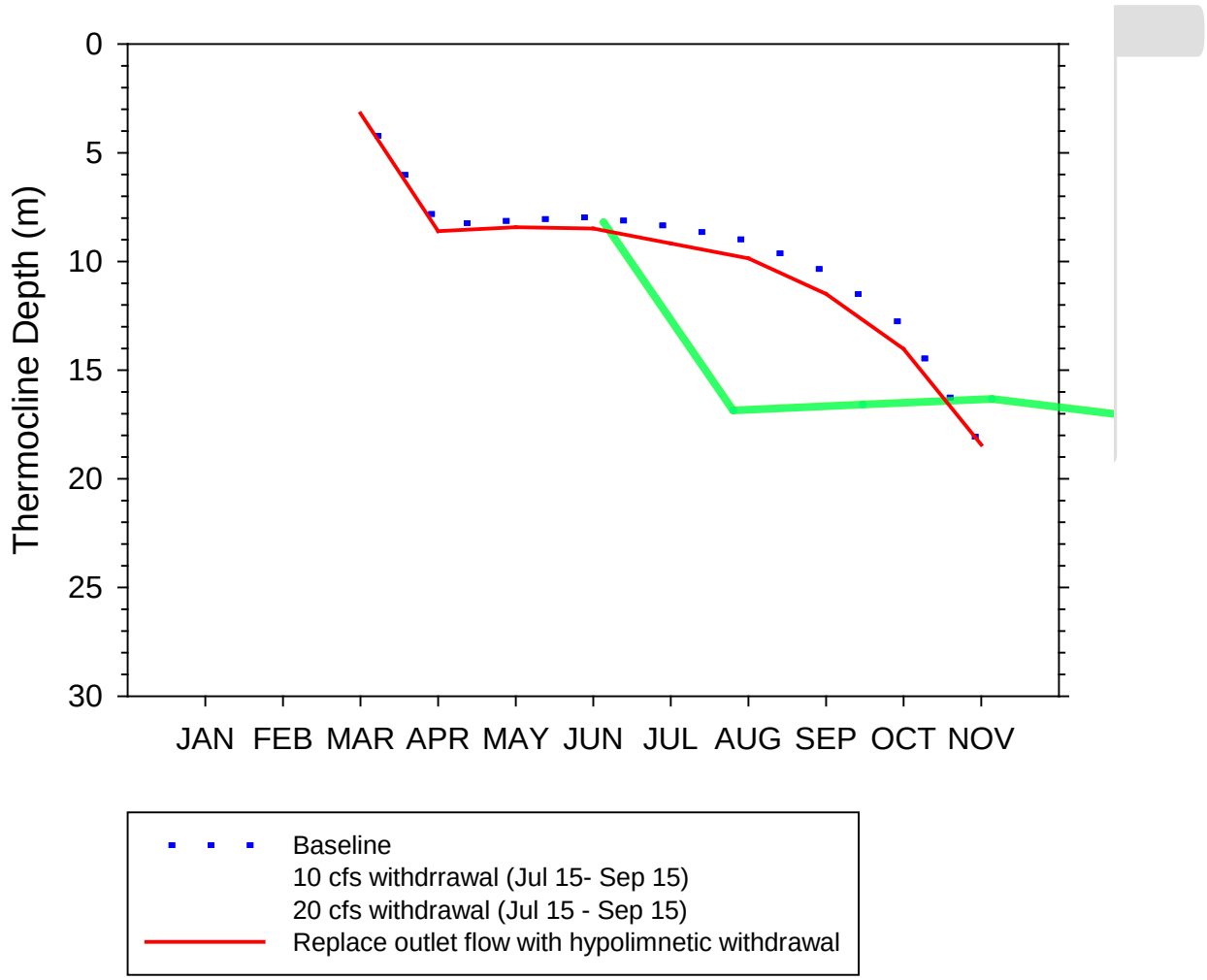

Figure 2. Monthly averaged thermocline depths based on the eight years of output from the 2-D CE-QUAL-W2 Lake Sammamish model.

3.1.2 Schmidt Stability

There appeared to be no significant effect of a July 15-September 15 hypolimnetic withdrawal on lake thermal stability as measured by the Schmidt stability index. Monthly average Schmidt stability (1995-2002) was essentially the same for the Baseline, 10 cfs, and 20 cfs withdrawal scenarios (Figure 2). Replacing the outlet withdrawal with a year-round hypolimnetic withdrawal did have a small effect on Schmidt stability (increased) (see Figure 3).

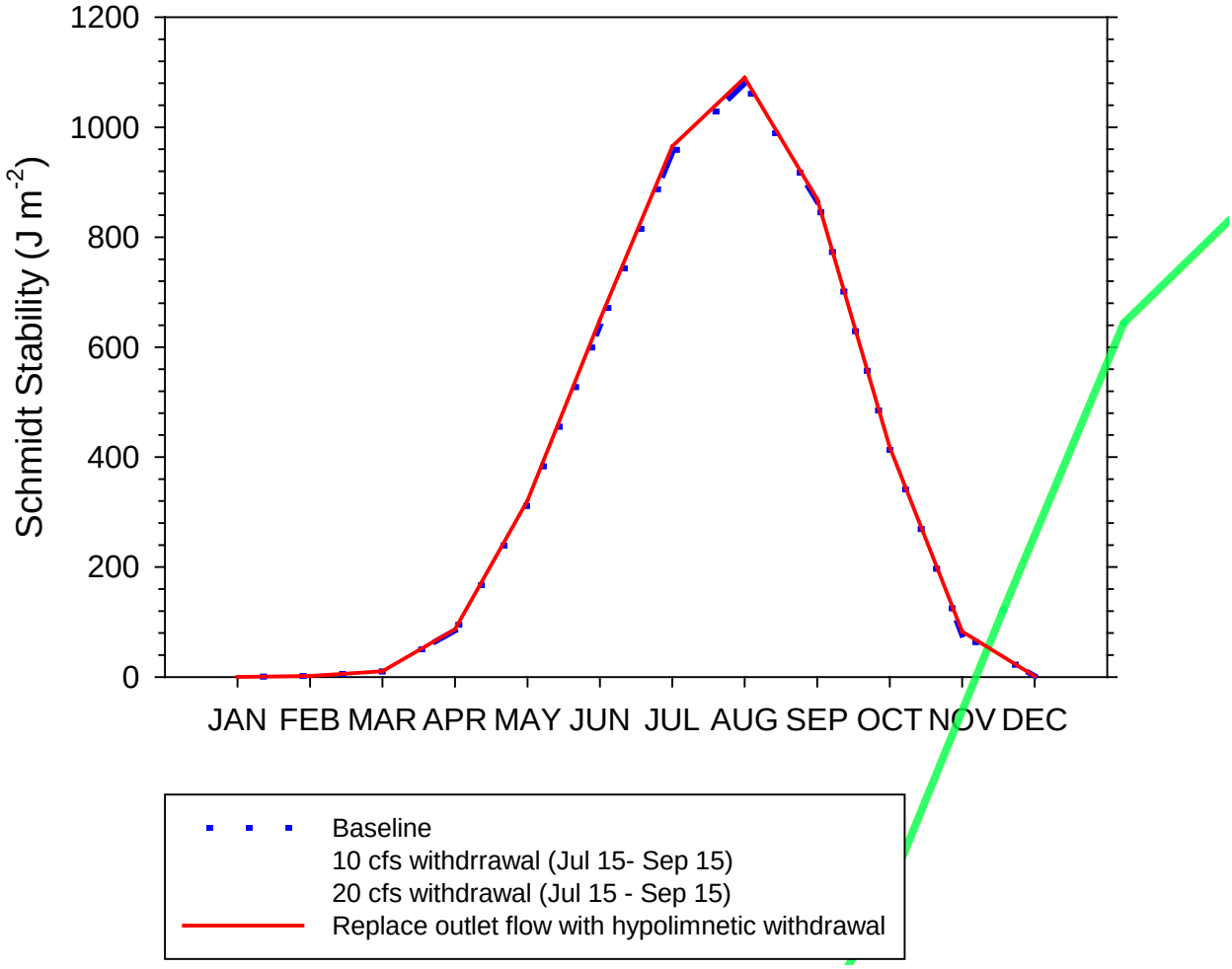

Figure 3. Monthly averaged Schmidt stability based on the eight years of output from the 2-D CE-QUAL-W2 Lake Sammamish model.

3.1.3 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 4).

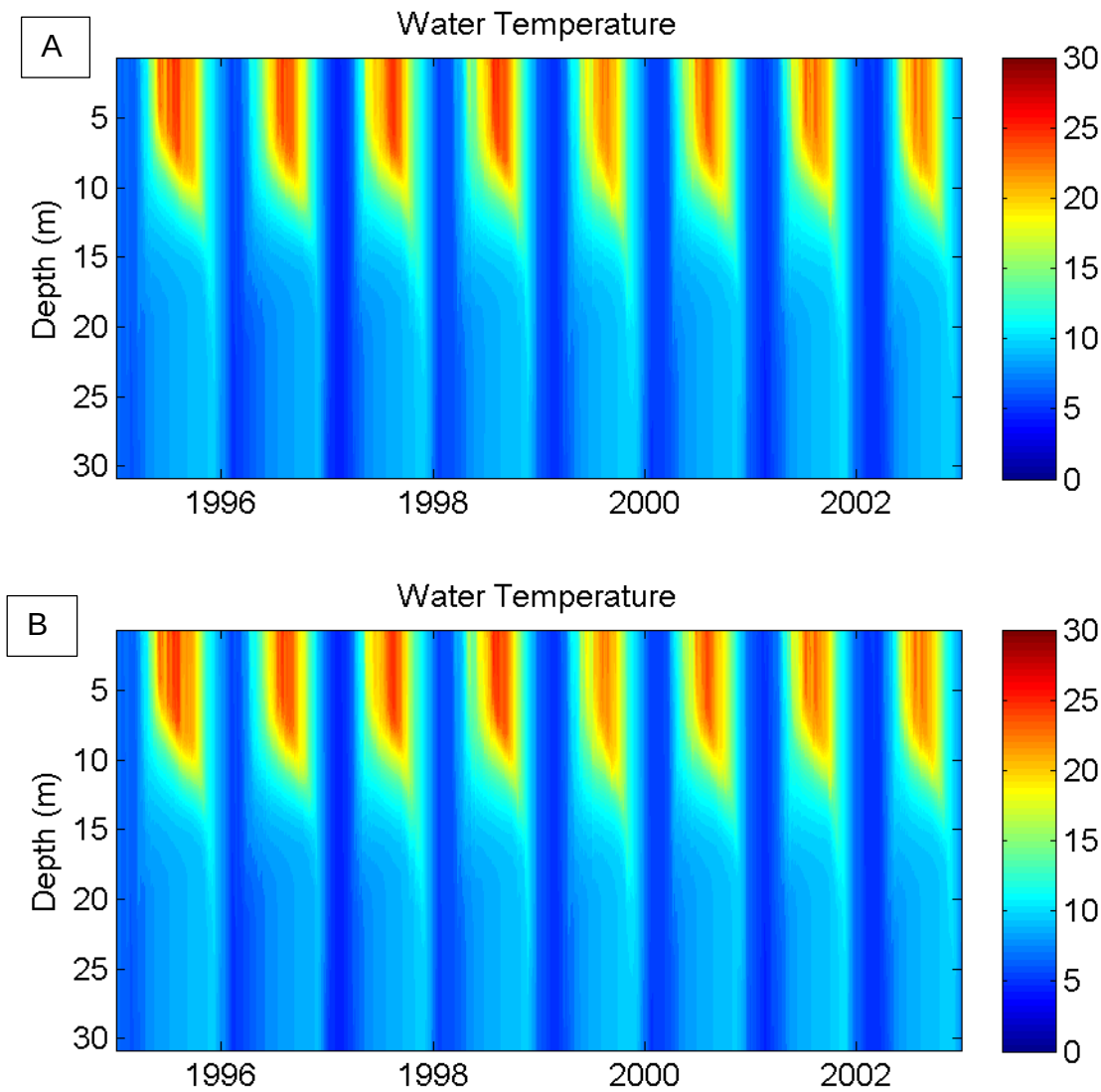

Figure 4. Color contour depth vs time (1995-2002) plots of lake temperature at the central lake station (0612) based on the 2-D model: (A) is the baseline model run, (B) is the 20 cfs hypolimnetic withdrawal scenario.

3.2 17 °C Isotherm

There appeared to be no significant effect of a July 15-September 15 hypolimnetic withdrawal on the 17 °C isotherm (Figure 5). The monthly average 17 °C isotherm (1995-2002) was essentially the same for the Baseline, 10 cfs, and 20 cfs withdrawal scenarios (Figure 5). Replacing the outlet withdrawal with a year-round hypolimnetic withdrawal did have an apparent effect on the depth of the 17 °C isotherm (deepening) (see Figure 5).

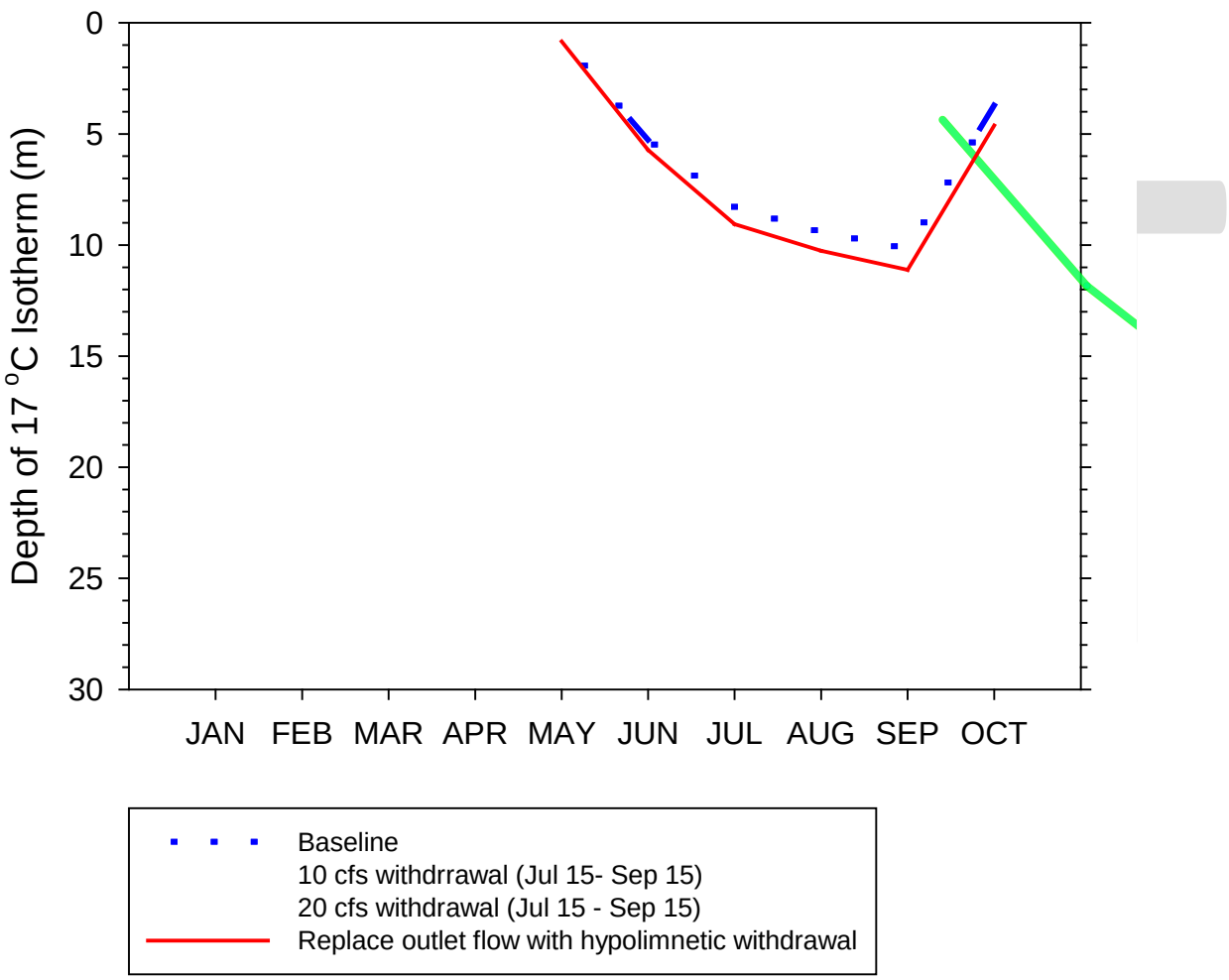

Figure 5. Monthly averaged 17 °C isotherms based on the eight years of output from the 2-D CE-QUAL-W2 Lake Sammamish model.

3.3 Favorable Habitat Volume for Kokanee

There appeared to be no significant effect of a July 15-September 15 hypolimnetic withdrawal on the monthly average favorable habitat volume for kokanee (Table 1 and Figure 5). Reductions in monthly average favorable habitat volume were half a percent or less in August, September and October with no significant changes predicted in other months (Table 1). Replacing the outlet withdrawal with a year-round hypolimnetic withdrawal had a more substantial effect on the predicted amount of favorable habitat volume with reductions as large as almost 5 percent (see Table 1).

Table 1. Average monthly (May-October) favorable salmonid habitat volumes (shown as percent of total lake volume) predicted by the 2-D CE-QUAL-W2 Lake Sammamish model for each of the three temperature thresholds.

Scenario	May	Jun	Jul	Aug	Sep	Oct
Baseline	95.7	67.6	42.7	27.7	15.8	50.5
10 cfs hypolimnetic withdrawal (Jul 15-Sep 15)	95.7	67.6	42.7	27.5	15.5	50.2
20 cfs hypolimnetic withdrawal (Jul 15-Sep 15)	95.7	67.6	42.7	27.4	15.3	50.2
Replace outlet with year-round hypolimnetic withdrawal	95.3	65.0	38.8	23.4	11.1	46.0

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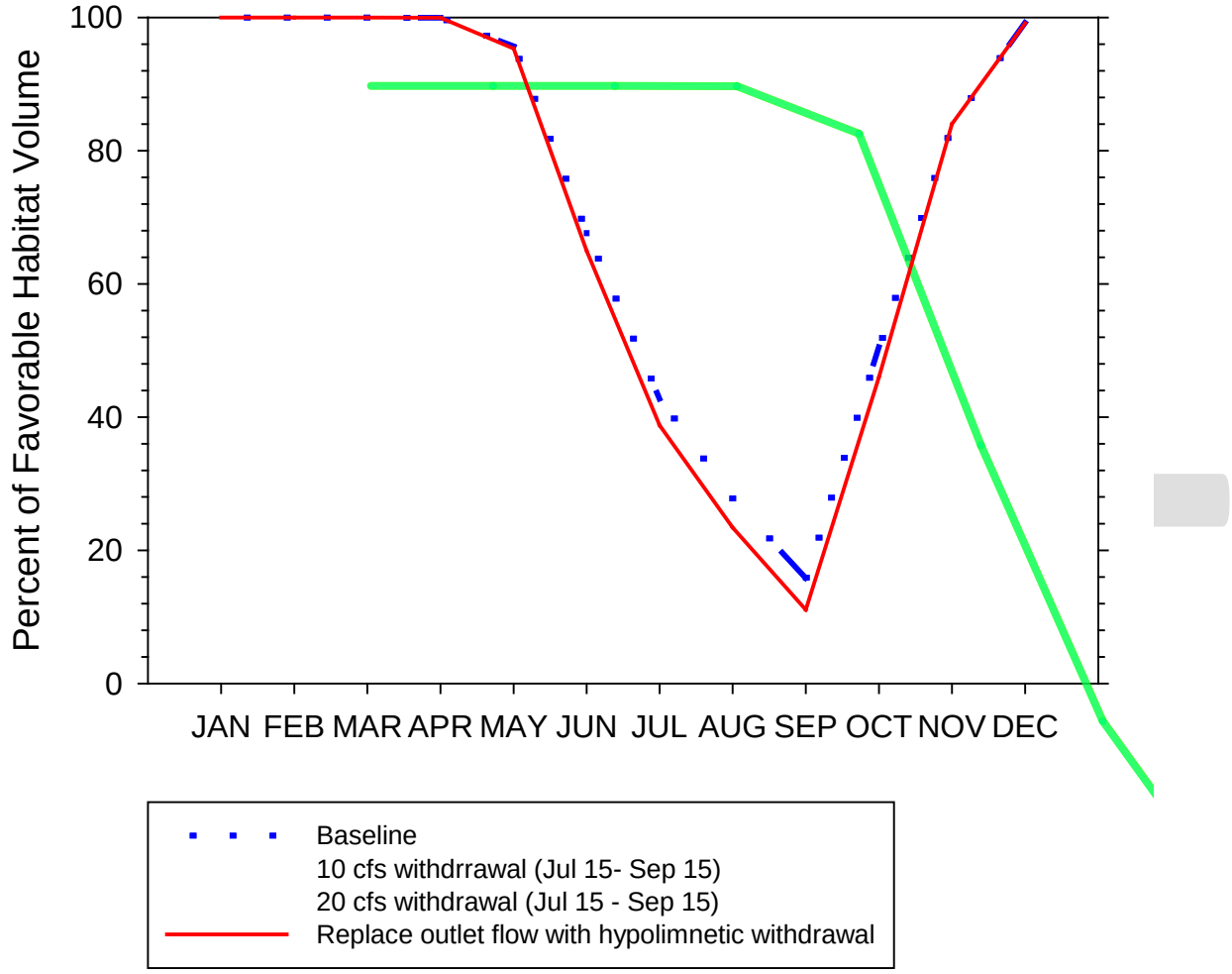

Figure 6. Monthly averaged favorable salmonid habitat volume based on eight years of ouput from the 2-D CE-QUAL-W2 Lake Sammamish model (volume <17 °C and greater than 4 mg DO per liter) isotherms based on the eight years of output from the 2-D CE-QUAL-W2 Lake Sammamish model.

4.0. CONCLUSIONS

Based on the 2-D modeling results, withdrawal of up to 20 cfs of water from the 15 m depth in Lake Sammamish between mid-July to mid-September (conceptually replacing the equivalent amount of lake outlet flow) does not appear to have a significant effect on lake thermal structure or significantly impact favorable lake habitat for kokanee. This is likely due to selective withdrawal of colder water below the thermocline as relatively strong lake thermal stratification is established by July with the seasonal thermocline established at a depth less than 15 meters until late September or October when the lake begins to cool and the thermocline begins to extend to the 15 meter depth or deeper (see Figure 2).

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