Phase 2.1 Report

Addressing Temperature and Dissolved Oxygen in the Lake Washington Ship Canal

June 2024

Acknowledgements

Treaty Rights

The Muckleshoot Indian Tribe and the Suquamish Indian Tribe each hold adjudicated treaty rights, which include the right to co-manage and harvest fish and other resources that originate from WRIA 8 at their respective usual and accustomed places (see U.S. v. Washington, 384 F. Supp. 312, 365-367 [W.D. Wash. 1974], 459 F.Supp. 1020, 1049 [W.D. Wash. 1978]) (Urgenson et al. 2021).

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Executive Summary

In June 2023, Long Live the Kings (LLTK)[1] and WRIA 8 Salmon Recovery Council[2] released Phase 1 Report - Addressing Temperature and Dissolved Oxygen in the Lake Washington Ship Canal. The report details the initial steps to identify solutions to low dissolved oxygen and high water temperatures impacting the health and migration of juvenile and adult salmon in the Lake Washington Ship Canal (LWSC). The initial steps of the Phase 1 process brought together groups with management authority or jurisdiction in the LWSC to:

1) Build and maintain consensus around the scope and priority of the problem
2) Gather expertise to identify potential solutions
3) Prioritize solutions

Together the group, referred to as the "Lake Washington Ship Canal Roundtable" (Roundtable) defined a common goal: Act urgently to improve juvenile and adult salmon health and survival in the Lake Washington Ship Canal by lowering water temperatures, increasing dissolved oxygen, and reducing abrupt transitions in those conditions.

In Phase 1, the Roundtable brainstormed 45 alternatives and categorized them in three ways. Category 1 alternatives are large-scale and merit additional consideration. Category 2 alternatives are related to the operations or infrastructure at the Hiram M. Chittenden Locks (a.k.a. Ballard Locks) and merit additional consideration. Category 3 alternatives are lower-ranked and were not selected for additional consideration because they were considered currently infeasible, highly uncertain, or unlikely to meet the Roundtable's goal.

Objectives for Phase 2 include:

1) Perform feasibility analyses of alternatives
2) Develop implementation and funding strategies
3) Establish necessary partnerships and authorizations
4) Support complementary efforts
5) Build broad regional support

Due to the immensity of these objectives, this report (Phase 2.1) addresses progress on these objectives, not their completion. As such, this report should not be confused as being a project proposal or a complete view of the feasibility of potential alternatives. Readers should use this information to begin to build a better understanding of how alternatives may impact water quality, could be implemented, and where more research or analysis is needed.

Specifically, Phase 2.1 advances our understanding of the feasibility of Category 1 alternatives, and implementation and funding strategies. Category 1 alternatives are large-scale and comprehensive

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[1] Long Live the Kings is a 501(c)(3) nonprofit with a mission to restore wild salmon and steelhead and to support sustainable fishing in the Pacific Northwest.

[2] The Lake Washington/Cedar/Sammamish Watershed (WRIA 8) Salmon Recovery Council is a regionally coordinated partnership among 29 local governments, community stakeholders, and scientists that oversees implementation of the science-based Chinook Salmon Conservation Plan.

strategies to achieve the goal and can be broadly described as engineered systems to cool water in the LWSC (further explanation in Phase 1 report). Alternatives in this category were conceptualized as either introducing cold water to the LWSC from another source or cooling the water through a closed-loop system, such as a heat exchanger. It is not feasible to cool the entire water column of the LWSC. Rather, Category 1 alternatives propose creating a cool water pathway near the bottom of the canal. The work assumes that this layer of cold water would provide a continuous pathway, or cold-water refuge, for migrating salmon. However, this salmon behavioral response would need to be confirmed through further research. While these alternatives would require large financial investments, they have the potential to generate significant benefits in addition to improved conditions for salmon health and survival. Potential co-benefits include shared heating and cooling infrastructure (i.e., district energy) and the other regulatory benefits associated with significantly improved water quality through the system.

LLTK contracted the services of Jacobs Engineering Group Inc. (Jacobs) and DSI LLC (DSI) to advance Phase 2.1. Jacobs took an engineering approach with a focus on a broad and conceptual analysis of cold-water sources and methods to convey cold water into areas of the LWSC. DSI completed hydrodynamic modeling to estimate the effect of cold water introduced at different locations and quantities. Jacobs also completed a high-level cost estimate of a conceptual alternative, a brief analysis of expected permitting, and research on potential funding pathways.

Cold Water Sources and Delivery Methods

Jacobs applied existing knowledge to identify potential sources of cold water near the LWSC, which included Puget Sound, ground water/aquifer, the Lake Washington hypolimnion, and mechanical water cooling (e.g. heat pump, cooling towers, etc.).

The most appealing source of cold water appeared to be water pumped from the hypolimnion of Lake Washington (the thermally stratified body of water deep in in lake)—as it is abundant, cold (7.5°C at 50 meters depth), and on the upstream side of the LWSC. The challenge is distributing the water efficiently through the LWSC, but this issue isn't necessarily unique to this cold-water source as most cold-water sources would need to be distributed through the canal passively (having denser cold-water flow with the canal's bathymetry), with a system of pumps and pipes, or a combination of the two.

As a water source, groundwater and aquifers in the area are relatively well understood. Groundwater appeared to have minimal utility as the availability in the proximity of the LWSC is low and may only be useful if attempting to cool a very small area of the LWSC.

Puget Sound has abundant water that is relatively cooler compared to the LWSC, but directly pumping marine water into the LWSC at quantities significant enough to impact the LWSC's temperature would have significant negative impacts to Lake Washington's ecology due to the salinity levels of Puget Sound waters. Given this, Jacobs considered a closed-loop heat exchanger in Puget Sound. The system would transfer heat from LWSC water to Puget Sound by circulating it through a heat exchanger in Puget Sound and pumping it back into the LWSC. While technically feasible, it did not appear advisable considering that very cold water (~12°C in August) is relatively deep (~100 meters), and about two miles west of the Ballard Locks. If you also consider the difficulties and associated cost of constructing and maintaining this type of infrastructure in the marine environment, along with other potential complicating factors, Puget Sound is not an appealing source of cold water for the LWSC.

Mechanical cooling appeared to be a technically feasible method to cool the LWSC and there are different systems that may be used, which would all have different feasibility considerations. However, to cool the quantity of water necessary to substantially impact the LWSC's temperature for the benefit of salmon, the industrial cooling system would need to be very large and custom-built. All other factors being equal, mechanical cooling was also considered to have higher operating costs for each unit of cooling compared to pumping cold water into the LWSC. Higher costs may be offset by design specifics – location, method, and multiple users to create economies of scale. For these reasons, mechanical cooling may be most suitable for a smaller segment of the LWSC that is not proximal to a preferable cold-water source.

Hydrodynamic Modeling

DSI completed hydrodynamic model refinement and calibration. The model produced outputs on water flow, temperature, and salinity, but did not predict nutrient dynamics. LLTK and DSI consulted with regional technical experts on the model calibration and incorporated feedback. Calibration was made particularly difficult by the anthropogenetic influence of the Ballard Locks. While model calibration could be improved, especially with additional data collection, the model performance was sufficient for this conceptual analysis.

Jacobs, LLTK, DSI, WRIA 8, and other technical experts identified three scenarios to model where water from Lake Washington was discharged[3] through diffusers at different quantities and locations.

Scenario	Discharge to Montlake Cut (CFS)	Discharge to Fremont Cut (CFS)	Total Discharge to LWSC (CFS)	Percent of LWSC supplemented [4]
1[5]	100	0	100	25%
2	300	0	300	74%
3	200	100	300	74%

Table 1. Scenarios run through the DSI model for discharging water from Lake Washington into the LWSC.

The initial model run (Scenario One) predicted cooling benefits that were mainly limited to the area of the LWSC east of Lake Union. Scenario Two amplified the results seen in Scenario One, bringing some cooling benefits west of Lake Union. Scenario Three appeared to produce cooling benefits that would be best for salmon. For instance, at 40 feet below the water surface at the Fremont Bridge, Scenario Three reduced the number of days during August above 19°C from 89%-100% of days to 0%-8% of days. The cooling benefits from Scenario Three extended from the

[3] Scenario One included an additional 25 CFS of water pumped to diffusers east of the Montlake Cut and Scenario Two and Three included an additional 50 CFS in the same area.
[4] Based on 405 CFS as total flow from the Ballard Locks during summer, low flow period.
[5] Referred to as "1b" in the DSI modeling report.

Montlake Cut west through the Fremont Cut and appeared to be obstructed by denser saltwater closer to the Ballard Locks known as the "saltwater wedge."

All modeled scenarios highlighted additional questions about hydrodynamics in the LWSC, which are summarized in the Potential Next Steps section below. With additional modeling that experiments with discharge locations, water quantities, or diffusers, the total amount of flow may be reduced while still creating water quality impacts that would be similarly beneficial to salmon.

Conceptual Design

Based on the assumptions from Scenario Three hydrodynamic modeling, Jacobs conceptualized a potential system that would use barge-based pumps to convey water to Montlake Cut and Fremont Cut using two separate pipes. The complete system also included oxygenation systems to saturate pumped water with dissolved oxygen, and an aeration system to destratify saline water near the Ballard Locks. Based on this highly conceptual stage of analysis, the system appears technically feasible, but a more systematic alternative analysis and value engineering exercise is advisable. Furthermore, quantifying potential benefits to salmon would require additional analysis, and likely data collection. Based on this additional information, we would expect any proposed system to be designed differently, so Jacob's analysis should not be interpreted as a proposal.

Jacob's initial cost estimate suggests capital costs of the potential system to be between $477 million and $954 million, with an estimated annual operating cost of $11 million. These estimates are highly preliminary and are intended to help define the overall scale of the solution. The estimates are not intended to be used for specific comparisons as the project specifications and estimates need further refinement before any such exercise is completed. While these costs are significant, they are comparable to other intractable fish passage problems, such as removal of the four lower Snake River dams, Howard Hanson Dam fish passage, or addressing fish passage at the Hood Canal Bridge.

An initial analysis of funding pathways and permitting is also included in the full report from Jacobs.

Potential Next Steps in Phase 2

There are several possible next steps based on the reports from Jacobs, DSI, and regional technical experts. Potential next steps are listed below.

Hydrodynamics

H1	Model fine-scale disruptions to the direction of LWSC water flow in response to cold water pumping to identify areas that may negatively impact salmon migration, especially juvenile outmigration. This may require additional data collection using an acoustic doppler current profiler (ADCP). It may also include further analysis of sub-surface barriers.

H2	Model water temperature changes associated with raising water levels in Lake Washington and Union by 2.7 meters (pre-Ballard Locks water level) to understand the modern-day water quality impacts of the Ballard Locks and LWSC.
H3	Better characterize interactions between the movement of cold water west and the "saltwater wedge" that is present in the western portion of the LWSC. A closer look at destratification methods and feasibility may also be required.
H4	Model the impacts of water withdrawal from Lake Washington's hypolimnion including temperature, depth of cold water, light transmission, nutrients, dissolved oxygen, climate change scenarios, and other factors.
H5	Expand the model's temporal perspective by calibrating it with data from additional years. Also, study modeling temperature changes in the future considering climate change.
H6	Expand the model to include dissolved oxygen model outputs and nutrient changes.
H7	Model the impacts of propwash on water quality.
H8	Model the impact of a mechanical cooling method – a heat exchanger near Foss Shipyard associated with a potential district energy system for commercial buildings near Seattle Pacific University.
H9	Better understand the potential complimentary benefits of shading over the water in terms of the potential cooling benefits and implementation costs.
H10	Analyze model outputs in additional ways, such as: - Calculate the change in model grid cells above a certain temperature threshold - Standardize model output graphs on the same timeframe - Create more animations to show changes over time - Provide statistical comparisons for seasonal periods, instead of full years

Systems Feasibility

S1	Explore the feasibly between land vs. barge-based pump station.
S2	Define navigational constraints for piping or other infrastructure.
S3	Investigate the feasibility and cost of piping vs. trenching for cold water conveyance.
S4	Advance the feasibility of oxygenation by creating a plan for a pilot project and characterize oxygen depletion.

Salmon Behavior

B1	Refine the understanding of adult and juvenile salmon behavior in response to changes in LWSC water temperature, dissolved oxygen, and salinity. This may involve significant data collection and habitat suitability modeling. - Design an experiment measuring the salmon response to a temporary cold-water input (treatment) into the LWSC - Collect fine scale fish movement and water quality data to detect salmon responses to natural changes in water quality - Use existing data to model habitat suitability

Conclusion

There are multiple, technically feasible approaches to supplement the LWSC with cold water to improve water quality. And in the appropriate configuration, these approaches are likely to reduce the number of days salmon are exposed to higher water temperatures that are lethal and sublethal. All the approaches are large scale, complex, and will require significant capital and operating investments. There are three main areas for further investigation to refine the approach – hydrodynamics of the LWSC, feasibility and efficiency of cold supplementation systems, and predicting salmon responses to water quality changes. All these areas are critical, interconnected, and urgent. Given these characteristics, a solution will need to involve a highly collaborative, multidisciplinary, and high-capacity approach.

Several laws and treaties indicate that a resolution to high temperatures and low dissolved oxygen in the LWSC is unavoidable. Areas of the canal are 303(d) listed as Impaired due to high temperatures under the Clean Water Act. The LWSC is habitat for Chinook salmon listed as Threatened under the Endangered Species Act, and harvestable salmon is a requirement to satisfy tribal treaty rights.

Increasing atmospheric temperatures associated with climate change will only exacerbate these problems and salmon populations in the watershed are vulnerable to collapse. Steelhead have already been functionally extirpated from the watershed and the collapse of other salmonid populations will cause irreparable environmental, economic, and cultural harm. It may not be a question of *if* our community will need to advance these large-scale solutions, but rather a question of *how much time do we have* until the problem is significantly worse, or too late to solve.

Conceptual Engineering Report

Jacobs

Jacobs

Lake Washington Ship Canal Engineering Report

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Long Live the Kings

Lake Washington Ship Canal Engineering Report
March 4, 2024

Lake Washington Ship Canal Engineering Report

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Acronyms and Abbreviations

$	2024 U.S. dollar(s)
°C	degree(s) Celsius
°C/d	degrees Celsius per day
$>$	more than
$\leq$	less than or equal to
$\geq$	more than or equal to
AACE	AACE International (formerly the Association for Advancement of Cost Engineering)
cfs	cubic feet or foot per second
CWSRF	Clean Water State Revolving Fund
DNR	Washington State Department of Natural Resources
DO	dissolved oxygen
Ecology	Washington State Department of Ecology
EIB	environmental impact bond
FY	fiscal year
gpm	gallon(s) per minute
HOD	hypolimnetic oxygen demand
HP	horsepower
Jacobs	Jacobs Engineering Group Inc.
kW	kilowatt(s)
kWh	kilowatt-hour(s)
LLTK	Long Live the Kings
Locks, the	Hiram M. Chittenden (Ballard) Locks
LOX	liquid oxygen
LWSC	Lake Washington Ship Canal
m	meter(s)
m^3	cubic meter(s)
m^3/d	cubic meter(s) per day

MG	million gallon(s)
mg/L	milligrams per liter
MGD	million gallon(s) per day
mm	millimeter(s)
NOAA Fisheries	National Oceanic and Atmospheric Administration – National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollution Discharge Elimination System
O&M	operations and maintenance
O_2	oxygen
P3	public private partnership
PCSRF	Pacific Coastal Salmon Recovery Fund
SCL	Seattle City Light
SDCI	City of Seattle Department of Construction & Inspections
SDOT	Seattle Department of Transportation
SOD	sediment oxygen demand
TDH	total dynamic head
U.S.	United States
USACE	U.S. Army Corps of Engineers
UW	University of Washington
VFD	variable frequency drive
WDFW	Washington Department of Fish and Wildlife
WIFIA	Water Infrastructure Finance and Innovation Act
WRIA 8	Water Resources Inventory Area 8 or Cedar-Sammamish Watershed
WSDOT	Washington State Department of Transportation
WTD	King County Wastewater Treatment Division

1. Introduction

Long Live the Kings (LLTK) and Lake Washington/Cedar/Sammamish Watershed (or Water Resource Inventory Area 8 [WRIA 8]) Salmon Recovery Council are investigating the hypothesis that cold-water inputs to the Lake Washington Ship Canal (LWSC) can improve water quality for the benefit of juvenile and adult salmon. LLTK has hired a consultant (DSI, LLC) to refine a three-dimensional hydrodynamic model of Lake Washington, Lake Union, and the LWSC and run scenarios that iteratively adjust cold-water inputs (that is, location, temperature, and quantity) and describe the changes to LWSC temperatures and salinity. With this information, technical experts can better describe potential benefits to salmon and limitations of conceptual ideas.

1.1 Project Purpose

LLTK has requested Jacobs Engineering Group Inc. (Jacobs) to help LLTK and WRIA 8 with this project by providing technical assistance. Jacobs' role at this project stage is to help LLTK and WRIA 8 identify potential limitations and opportunities associated with cold-water inputs based on experience, available information, cost, and engineering judgement; the project purpose is *not* to develop or thoroughly evaluate all alternatives or eliminate alternatives or to eliminate alternatives at this preliminary stage. Due to budget limitations, Jacobs only cost-estimated one alternative, which was selected by LLTK and WRIA 8 in consultation with other partners and organizations. The project is currently focused primarily on LWSC temperature, with a secondary consideration for dissolved oxygen (DO). This is only an initial analysis.

1.2 Summary of Initial Findings

This section summarizes the science and engineering considerations for four cold-water sources informed by *Phase 1 Report – Addressing Temperature and Dissolved Oxygen in the Lake Washington Ship Canal* (LLTK and WRIA 8 Salmon Recovery Council 2023). Initial findings for each of the four cold-water sources, presented in relative terms, is as follows in Table 1-1.

Table 1-1. Initial Findings for Cold Water Sources

Cold Water Source	Initial Feasibility	Notes
Lake Washington hypolimnetic supplementation	Coldest naturally occurring source; proximal to LWSC's east side; sufficient quantity	Potential to cool the canal with appropriate distribution piping and pump size
Pump from aquifer	Low-water availability proximal to LWSC (less than 10 percent of required cooling flow); consumptive water rights barrier	Potential to cool very small, hyperlocalized area
Heat pump	Requires highly specialized heat pump, unlikely to provide flows sufficient to cool entire LWSC, high electricity demand	Potential to cool a LWSC section with costs likely more expensive than hypolimnetic supplementation
Heat exchange	Cold saltwater approximately 2 miles from LWSC's west end; would require challenging deep-water marine construction and maintenance	More piping, engineering complexity, and operational costs compared with hypolimnetic supplementation; could be more practical for localized areas in LWSC's west end

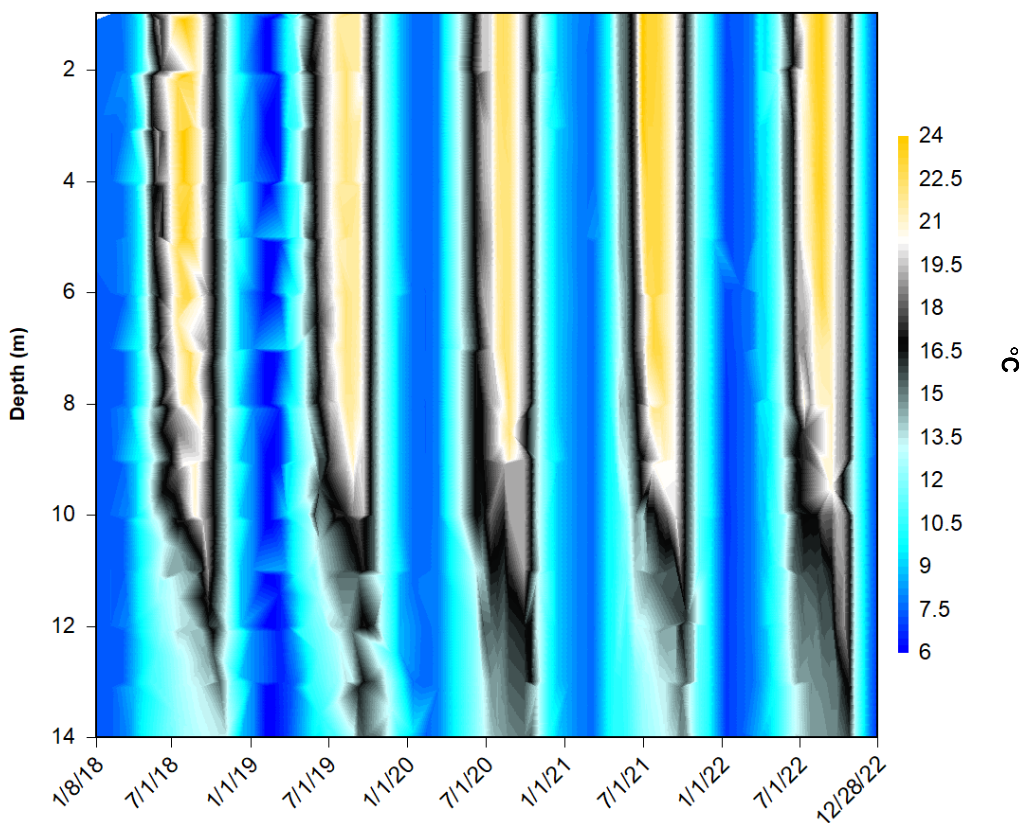
The purpose of this initial analysis was to inform the project's modeling effort and to prepare the engineering team to help identify an alternative to cost estimate. Note that some combination of cold-water sources and distribution solutions, or multiple discrete solutions, may ultimately be required to achieve acceptable conditions in the LWSC.

2. Background

Synthesis of Best Available Science: Temperature and Dissolved Oxygen Conditions in the Lake Washington Ship Canal and Impact on Salmon (King County and WRIA 8 Salmon Recovery Council 2021) determined that protection of the salmon in and around the LWSC requires cooler water and higher DO. A targeted lower bottom water (hypolimnetic) temperature combined with sufficient DO may have the potential to improve salmon migration success. A workshop led by LLTK and the WRIA 8 Salmon Recovery Council, explored solutions to "lethal and sublethal temperatures and dissolved oxygen (DO) conditions" in the LWSC (LLTK and WRIA 8 Salmon Recovery Council 2023).

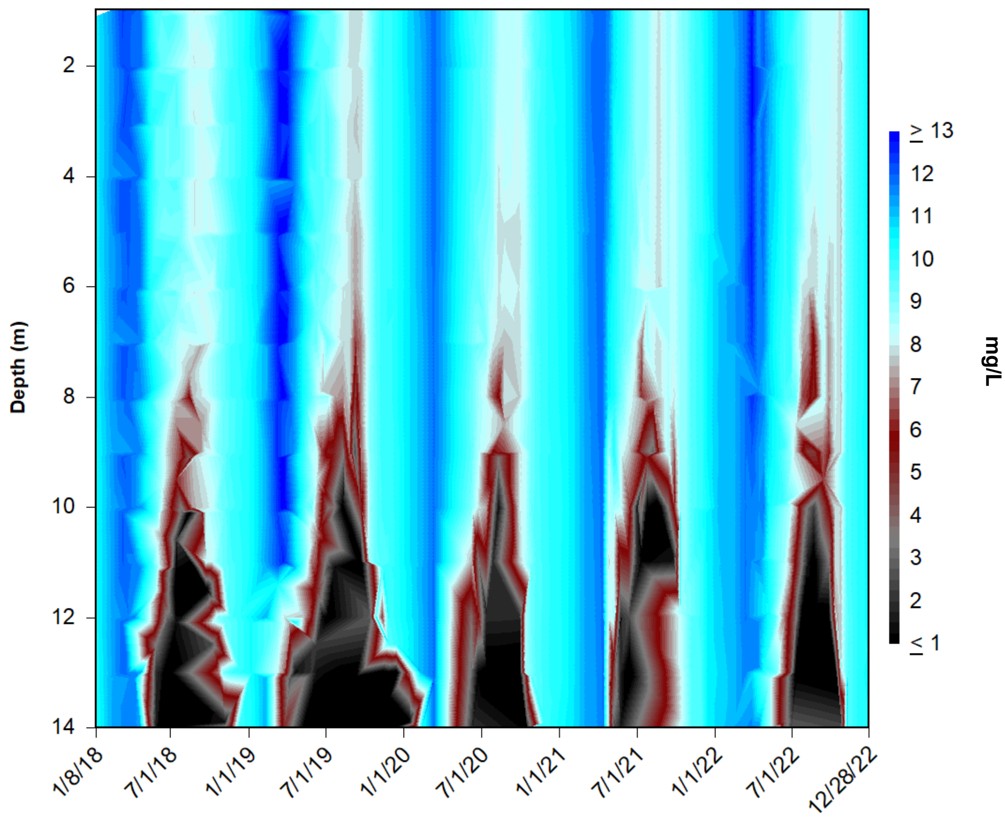
The coolest water in the LWSC is in the Lake Union hypolimnion, but the temperature below the Lake Union thermocline commonly exceeds the 15 degrees Celsius (°C) sublethal temperature threshold from mid-summer to mid-fall (Figure 2-1). Due to a combination of high temperature and shallow depth, some areas of the LWSC do not appear to stratify during the late summer and early fall. Concurrent with the problem of temperature is low DO; while salmon are severely temperature-stressed below the thermocline, the DO concentrations are sublethal to lethal at the same time under the Lake Union thermocline (Figure 2-2). This temperature and DO habitat squeeze is a key limiting factor for salmon in the watershed.

Figure 2-1. Lake Union Temperature Profile at Sampling Station A522



Notes:
°C = degrees Celsius
m = meter(s)

Figure 2-2. Lake Union Dissolved Oxygen at Sampling Station A522



Notes:
≥ = more than or equal to
≤ = less than or equal to
m = meter(s)
mg/L = milligrams per liter

Generally, both the temperature and DO problems must be addressed to correct water quality in this critical salmon habitat. Proven methods of hypolimnetic oxygenation, using pure oxygen (O_2) or other methods, can increase DO and preserve thermal stratification. Temperature is, therefore, the more complicated and important problem to address and solutions to address DO can be added to almost any cooling approach.

Regardless of the method of cooling, this analysis assumes that a cold-water layer in the LWSC approximately 1 meter thick will be sufficient to support fish health; this should be confirmed with biologists, additional data collection, and the model updated as necessary to confirm the final design scenario provides sufficient ecological benefit.

3. Additional Considerations for Cold Water Sources and Distribution

The following represents initial analysis performed regarding technical topics as described in the project scope and verified in the project workshop with LLTK and WRIA 8 staff on April 17, 2023. This analysis is intended to further define and advance the concepts presented in the *Phase 1 Report – Addressing Temperature and Dissolved Oxygen in the Lake Washington Ship Canal* (LLTK and WRIA 8 Salmon Recovery Council 2023). Technical topics presented are broadly categorized as potential cold-water sources and delivery methods; note that delivery methods are not necessarily exclusive to particular cold-water sources, and more than one cold-water source and/or delivery system may ultimately be required to provide acceptable conditions within the LWSC. Further analysis and concept refinement of the Lake Washington hypolimnion supplementation concept is presented in Section 4.

Physical limnology and bathymetry will govern the hydrodynamics of cold-water introduction, regardless of the source. Cold water pumped into the LWSC will sink or float to the same density water in the LWSC. This conceptually simple dynamic is complicated by the introduction of marine water from the Ballard locks. The inflow point(s) of water would be designed to minimize mixing, with some form of diffusion likely required to minimize mixing. The assumed goal is to create a continuous layer of cold water for salmon migration and, therefore, minimal mixing would improve the efficiency of the system. This layer of cold water must exist from Union Bay to the Hiram M. Chittenden (also known as Ballard) Locks (the Locks). The modeling portion of this project will investigate the details of how this layer can be created.

Lake Union may be the major sink for cold water. Assuming the creation of a 1-meter-thick cold-water layer with sufficient DO, the volume of this layer would be approximately 2.3 million (M) cubic meters (m^3) (608 million gallons [MG]). Heat gain and DO loss in Lake Union will strongly inform the design pump rate and inflow hydraulics; modeling is required to determine the length of time to 'fill' Lake Union with cold water and determine the ultimate impact of Lake Union on the larger cooling concept. Further modeling is required to confirm that pumping cold water earlier in the year would introduce enough cold water to Lake Union to overcome heat gain and other water quality issues in the summer.

The velocity of the backflow of cold water through Union Bay is another key consideration. Smolts move downstream, not upstream, drifting or swimming with the current (Katzman et al. 2010). The impact of flow into Lake Washington on juvenile migration to Puget Sound will need quantification to ensure that design or operation of pumped flow does not create backflow or otherwise inhibit smolt movement west toward the LWSC.

3.1 Potential Sources for Cold Water

The cold-water sources investigated include the following; however, several variations of these alternatives could not by analyzed specifically, but these sources provide a conceptual look at the approach:

- **Hypolimnetic supplementation from Lake Washington—**Pump cold water from the hypolimnion of Lake Washington and distribute in the LWSC.
- **Pump from aquifer—**Pump cool water from the groundwater aquifer adjacent to the LWSC and distribute in the LWSC.
- **Heat pump—**Use a heat pump to extract heat from warm LWSC water and return the cooled water to the LWSC; reject heat to geothermal wells, sanitary sewer, air, or other source.

- **Heat exchange—**Pump cold saltwater from the Puget Sound, pump warm water from the LWSC, use a heat exchanger to cool the freshwater, return saltwater to the Puget Sound, and distribute cooled freshwater to the LWSC.

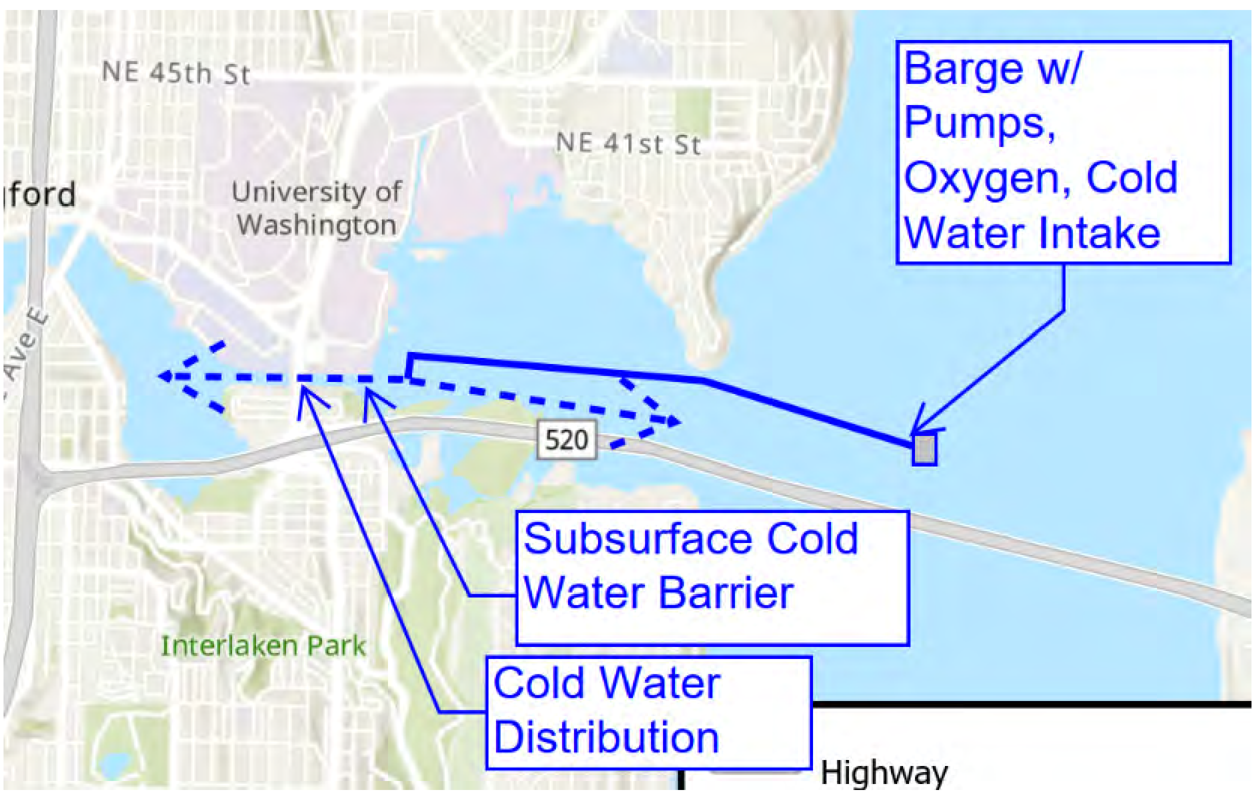
District Energy [cooling] is not a potential source of cold water but is a potential variation to all cold-water sources. It would share intake, pumping, and other functions but may also increase the total demand for cool water. The initial district energy concept is proposed for the University of Washington (UW) Seattle campus; because of the UW's location next to Lake Washington, hypolimnetic withdrawal is the most likely water source for the UW campus district energy project.

District [Energy] Heating could remove heat from the LWSC to create warm water or steam for a campus or other district energy system. While not directly related to other cold-water sources discussed in this engineering report, this could be a separate solution that might help the overall conditions in the LWSC. A district energy facility west of Lake Union could be of value, as the hypolimnetic supplementation concept from Lake Washington appears less effective west of Lake Union. District energy options are further discussed in Section 3.6. Cold-water sources are described in further detail in the following four subsections.

3.2 Hypolimnetic Supplementation from Lake Washington

Lake Washington is the second largest natural lake in Washington state. A thermocline sets up between 10-meter and 15-meter depth. Average depth is 33 meters, maximum 65 meters. It has a hypolimnetic volume of 1.77 cubic kilometers (Arhonditsis et al. 2003). Pumping cold water from the Lake Washington hypolimnion to supplement cold water within the LWSC may be feasible (Figure 3-1).

Figure 3-1. Conceptual Schematic of Hypolimnetic Supplementation



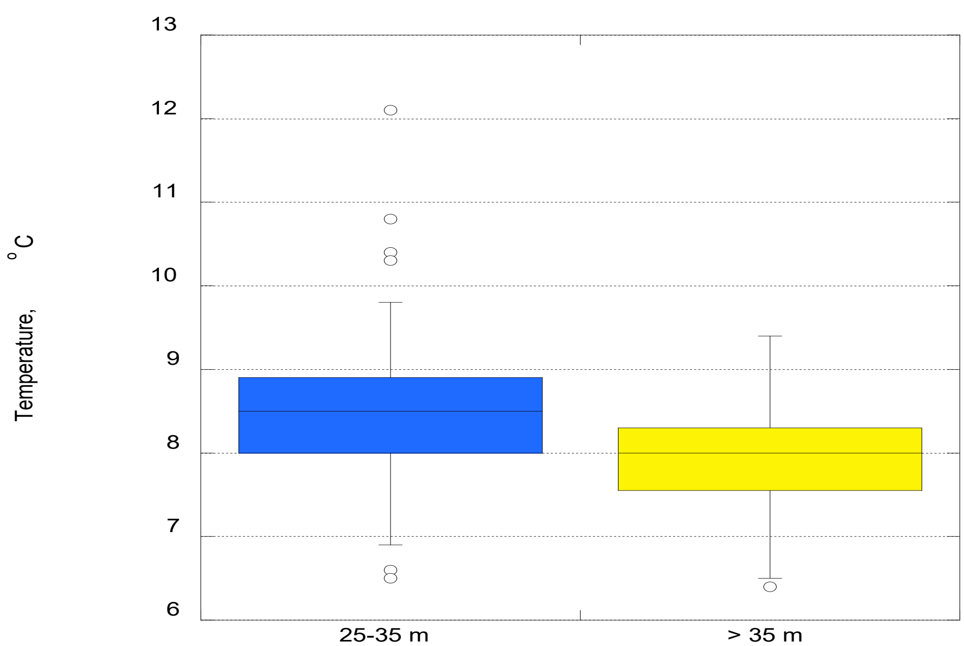
3.2.1 Temperature and Flow

Conceptually, hypolimnetic supplementation is the most straightforward option to implement (Figure 3-1). A pump station would have an intake located in the mid-hypolimnion of Lake Washington. The pump station could be on a barge or located on shore. The pump would discharge to the LWSC. A single point discharge west of a subsurface cold-water barrier would be preferred for simplicity of construction compared to pipes extending far into the LWSC.

A flow of 125 cubic feet per second (cfs) or approximately 70 million gallons per day (MGD) was suggested as an initial flow rate for modeling and conceptualizing alternatives, but initial modeling suggests that 125 cfs will not provide sufficient cooling in the LWSC. For reference, a 100-MGD pump station drawing from the hypolimnion would transfer 0.21 percent of the hypolimnion volume per day from the hypolimnion to the LWSC. The hypolimnetic withdrawal would not result in a net increase in water consumption from Lake Washington, but it would change the temperature of the water that was removed from the lake via discharge from the Locks. Preliminary modeling indicates this withdrawal and distribution of water would not create a backflow effect between the intake and distribution points.

The coldest available water from Lake Washington is approximately 7.5°C from a depth of approximately 50 meters or greater. However, peak hypolimnetic temperatures near the bottom may be greater than 9°C in some years. The temperature at 25-meter to 35-meter depth is only marginally higher than at the bottom (Figure 3-2). A preliminary intake depth of 25 meters to 35 meters is recommended to offer construction economies and intercept water with higher DO.

Figure 3-2. Hypolimnetic Temperature Comparison by Depth, 2018 through 2022



Source: WABUOY (April 1, 2018 through April 1, 2023).
Notes:
> = more than
°C = degrees Celsius
m = meter(s)

3.2.2 Dissolved Oxygen

Appendix A details DO issues and solutions. In summary, O_2 can be injected into the hypolimnion of Lake Union and into water pumped from the hypolimnion of Lake Washington. In Lake Union, O_2 injection is needed to restore habitat and prevent loss of DO from water pumped from the hypolimnion of Lake Washington. There is a hypolimnetic O_2 sag in Lake Washington; it is not habitat critical but provides little to no margin for DO depletion in water pumped into the LWSC. Consequently, pumped water up may need to be brought to DO saturation to provide that margin.

In summary, the most likely depth of withdrawal from Lake Washington would be the mid-hypolimnion (25 meters to 35 meters). The coordinates of the location will depend on where it is either most convenient to locate a barge pump station or an intake for a pump station on land. Further modeling should be performed to confirm that pumping will not significantly reduce the depth or location of the cold-water supply by altering the hypolimnion.

3.2.3 Pump Station Type and Location

This analysis is not intended to prefer a barge-based or land-based pump station; further analysis and investigation are required to determine a final pump station location. While a land-based pump station would simplify operation and logistics, shoreline real estate in this area may not be available, may be prohibitively expensive, or may not be allowed to be used as a pump station for land use or environmental reasons. A barge-based pump station would solve some engineering challenges, may be more cost-effective, or may provide a permittable interim option while a permanent land-based pump station is designed, permitted, and constructed. A barge also creates significant navigation concerns, adds complication to pump power supply, and would add challenge to pump and other maintenance. The following sections elaborate on options for a barge-based or land-based pump station.

3.2.3.1 Barge Pump Station

A barge-based pump station for the Lake Washington hypolimnion supply would presumably be moored in Lake Washington, near or over the intake. The following are known attributes or challenges associated with implementing a barge-based pump station:

- O_2 generation would be required on the barge if O_2 was to be injected directly into the pumped water. Shore power would be required for the pump station and O_2 generator. Refer to Appendix A for further description of potential O_2 generation systems.
- The barge could presumably be moored for the winter for storage and maintenance if operating the pump year-round provided no benefit.
- A barge would protect the intake and create the opportunity to suspend the intake from the surface. Locating pumps near the intake would also reduce the length of intake pipe required and simplify pumping design.
- A barge would require coordination with the United States (U.S.) Army Corps of Engineers (USACE) and with the U.S. Coast Guard regarding vessel navigation and would also require permits from Washington Department of Fish and Wildlife (WDFW) to create an over-water structure. Further detail regarding potential permits required and associated timelines are presented in Part 4.
- Access to the barge would require use of a boat, increasing operations and maintenance (O&M) burden and requiring additional safety protocols.

3.2.3.2 Land-Based Pump Station

A land-based pump station would resolve many of the challenges of a barge but would create new challenges including siting on an urban shoreline, land acquisition cost, land use and building permitting, and hydraulic challenges due to the pump station being relatively far from the intake. A different strategy for suspending the intake above the lakebed would also be required if the intake is not supported from the surface by a barge.

3.2.4 Fish Screens

Requirements for intake fish screens, pump energy, and distribution systems for the Lake Washington hypolimnetic withdrawal would be similar regardless of the pump station location. Because the preliminary estimated pumping rate is greater than 100 MGD (154.7 cfs), fish screens complying with National Oceanic and Atmospheric Administration (NOAA) fish screening criteria for a lake diversion application will be required. To protect aquatic life from both impingement and entrainment from the pumped water system, the maximum approach velocity needs to be 0.2 foot per second with the maximum screen slot opening size no greater than 1.75 millimeters (mm). This requires a relatively large fish screen with at least 775 square feet of screened surface area. The fish screens could either be hung from a barge or secured to the lakebed.

The actual type of fish screens would vary depending upon either a barge pumping plant or a land-based pumping plant. The most practical screening technology for this size intake are cylinder screens. For a barge pumping application, using 100 MGD as a reference point, four 9 feet tall x 7 feet diameter cylinder screens would be used with one 50 cfs vertical turbine variable frequency drive (VFD) pump per intake screen. For a land-based pumping plant, two 7 feet diameter by 26 feet long Tee screens secured to the lake floor would likely be used. In either case, the discharge pipe would likely be at least a 6 feet diameter conveyance pipe to limit velocities and energy losses. The number and/or size of facilities described would increase for larger flow rates.

3.2.5 Representative Energy Requirements

The following assumptions were used to estimate the initial power required to pump from Lake Washington:

- Required flow rate = 100 MGD (approximately 150 cfs)
- Total dynamic head (TDH) = 30 feet
- Pump efficiency = 65 percent
- To calculate required horsepower (HP) and kilowatts (kW) needed,
  HP = flow rate in gallons per minute (gpm) x TDH / 3,960 x pump efficiency
  = 69,580 gpm x 30 feet / (3960 x .65) = 811 HP
- To convert HP to kW,
  kW = HP x 0.7457 = 605 kW
- Assuming pumping rate at a TDH of 25 feet = 155 cfs,
  HP (kW) = 676 (490)
- Power cost = $0.15/kilowatt-hour (kWh)
- Cost = 490 kW x 24 hours/day x $0.15/kWh = $1,764/day, approximately $2,000/day

This example calculation was updated with the final cost estimate. Note that additional pump energy is required for the longer piped sections, and the pumped energy would also increase if pipe sizes were decreased for the same flowrate.

3.2.6 Piping and Outfall and Diffuser Options

The distribution piping ideally would be located in the channel where fish are likely to prefer access, and design must assess any potential conflicts with likely predators or existing structures and uses such as outfalls. Design must assess and mitigate potential navigation hazards during operation and construction. Pipe size and other design features can be adjusted to suit many constraints. Further analysis is required to determine if and how the distribution piping would be secured to the channel.

In-water work to install the pipe and diffuser would require permits from WDFW and potentially USACE, within approved in-water work windows. A permanent National Pollution Discharge Elimination System (NPDES) discharge permit may also be required from Washington State Department of Ecology (Ecology), and local permits from City of Seattle for critical areas disturbance, street improvements, and other parcel construction would also be required.

To exclude fish from the outfall, the outfall port design should consider elastomeric “duckbill” check valves (for example, Tideflex) with a dynamic port opening with size varying with flow. For simple ports with or without risers, aquatic growth can obstruct flow; design should consider potential for algae and shellfish to accumulate on the diffuser. Simple ports are likely to have a smaller footprint than duckbill check valves.

Check valves may increase cost and introduce higher head loss and will be avoided if possible. Further technical and regulatory considerations are required to advance the outfall and associated details including diffuser ports. Outfall pipe material (high density polyethylene versus steel) and anchoring systems require further consideration; corrosion, longevity, and ease of installation and removal will be considered. Regular inspections and maintenance will be required to ensure proper function (for example, clear aquatic growth on the structure and ports).

3.2.7 Siphon Alternative

During the alternative brainstorming process, a siphon was suggested as an approach to reduce electrical costs and siphons have been used in other deep-water cooling projects (Sullivan Lake). Because the cold water in Lake Washington is deeper than the cold water in the LWSC or Lake Union, a siphon would not convey the cold water out of Lake Washington into Lake Union and is not a feasible alternative to mechanical pumping in this case.

3.2.8 Critical Remaining Issues or Questions

Further investigation and analysis are required to determine whether a barge-based or land-based pump station would be feasible and which would be preferable. Availability and cost for land and permit pathway for a land-based pump station requires further analysis and investigation, particularly for land use and power supply. A site selection process, including coordination with Seattle City Light (SCL) to confirm power availability, would be required to identify, obtain, and develop a near-shore location for pump power transformation and supply. Feasibility and the permit pathway for locating a barge-based pump station in Lake Washington (or elsewhere) will require further coordination with the USACE, WDFW, and other impacted parties.

Further analysis is required to compare flowrates and locations of cold-water supplementation for the most beneficial configuration; allowable pipe size and location must be reviewed from permitting and cost perspectives. Further analysis is also required to determine if cold water must be pumped to the LWSC west of Lake Union, or if a different solution such as diffusion could be implemented to prevent the saltwater wedge from advancing to Lake Union without requiring long and expensive pipes from Lake Washington to Fremont.

Study and likely modeling of cold-water diffusers is required to determine if the diffusers can be shorted or simplified, and if backflow prevent can be removed. The impact of cold water discharged from the distribution system should also be considered regarding turbulence and potential disturbance of sediment. Impacts to water quality (nutrients) associated with conveying such large amounts of water must be considered. Because smolt only migrate downstream (with the water flow), analysis is required to confirm that the flows within applicable portions of the LWSC continue in the westerly direction to avoid impeding smolt travel. Refer to Part 4 for additional items requiring future coordination.

3.3 Pump from Aquifer

Instead of or in addition to pumping from the Lake Washington hypolimnion, the Roundtable conceptualized an alternative to pump cold water from the aquifer north (or south) of the LWSC, oxygenate, and distributed within the LWSC. Significant questions regarding this cold-water source include the ambient temperature and low DO of the groundwater, the magnitude of the infrastructure and restoration required, and uncertainty regarding if a water right would be granted by the Ecology.

3.3.1 Groundwater Recharge Volumes

An initial review of groundwater recharge volumes required to offset the pumped withdrawal suggests that this source option is infeasible at the scale (flow and volume) needed. For 100 MGD/150 cfs groundwater withdrawal rate over 6 months, initial calculations indicate that an aquifer recharge area of more than 30 impervious square miles, or more than one third of the total land mass of the City of Seattle, would be required to offset the volume of water withdrawn annually. Even if the storm drainage and combined sewer systems were modified to infiltrate the bulk of the stormwater runoff in the recharge area, which would be a very significant infrastructure investment, sufficient impervious area and runoff volume is not available. Further consideration of groundwater as the main source of cold water for the LWSC is not recommended.

This option, however, may be viable on a much smaller scale (with significantly smaller withdrawal volumes) to address a specific challenge such as providing cold water in a portion of Lake Union to some unique refuge area. For instance, infiltrating all of the stormwater runoff in approximately 1,200-acre area including Wallingford and the UW campus could potentially yield approximately 2,600 acre-feet per year; if all of this infiltrated runoff was pumped out of the ground over a 6-month period, the maximum average flow rate could be 7 cfs.

3.3.2 Issues for Future Consideration

This preliminary information is provided to inform future efforts in case a partial solution is provided via groundwater. Construction impacts and the location of wells, pumps, and conveyance piping within the City of Seattle right-of-way are significant issues to be resolved. Construction of conveyance piping alone within Seattle streets requires significant utility coordination, pipe design, and pavement restoration. Wells or pumps located within the right-of-way may require a term permit from Seattle Department of Transportation (SDOT). To avoid or at least share the cost and environmental impact of replacing viable existing pavement, a potential conveyance project should be coordinated with SDOT and other frequent street users such as Seattle Public Utilities or Puget Sound Energy to install piping in conjunction with other planned utility installation or pavement replacement projects. To avoid withdrawing water from the LWSC itself, groundwater may need to be withdrawn above the current lake level, with the base of pumped wells located above the LWSC surface elevation. A future project in combination or coordination with increased stormwater infiltration within the aquifer may address water rights concerns for a smaller-scale project.

3.3.3 Critical Remaining Issues or Questions

Critical remaining questions include viability of the Water Rights process with Ecology, and the cost of significant widespread improvements in the right-of-way. Completing this project in cooperation or partnership with a combined sewer overflow reduction (stormwater infiltration) project could provide cost sharing for right-of-way restoration costs.

The following additional issues and questions would require further investigation if a smaller groundwater withdrawal supplement system concept were to move forward in the future; these have not been further defined at this time, as a large-scale groundwater withdrawal option does not appear feasible:

- Yield of aquifer(s)
- Water quality and temperature of aquifer, including DO and other chemical parameters
- Well and pump station qualitative sizing, distribution piping, diffuser options, and energy requirements

3.4 Heat Exchange

A heat exchanger would use the relatively cold saltwater of the Puget Sound as a heat sink to cool the warm freshwater withdrawn from the LWSC. Saltwater and freshwater would not be mixed; a heat exchanger would allow energy exchange between the two water sources without physical contact of the two different liquids.

Cold water must be provided to the east end of the LWSC to encourage smolt migration. In the case of a heat exchange (cooling) option, warm water would be withdrawn from the west end of the LWSC, cooled in a heat exchanger, and pumped east throughout the length of the LWSC, to the terminus in Lake Washington. Potential intake issues and strategies, including fish exclusion, are like those described in Section 3.1 for the hypolimnetic supplementation option.

The main difference with cold freshwater distribution for this option versus the hypolimnetic supplementation option is that at least some of the cooled water would need to be pumped the full length of the LWSC to the Montlake Cut or to the eastern terminus of the dredged canal in Union Bay, unless this approach were to be combined with the hypolimnetic supplementation option to address a smaller portion of the LWSC west of Lake Union only. While likely increasing piping and pumping costs, one benefit of this option could be the ability to do more cooling near the Locks, avoiding the concern of cold water dissipating in the LWSC (or specifically in Lake Union) before reaching the critical area at the Locks. Another advantage of this concept is that withdrawing water from the west end of the LWSC and discharging it at the east end would increase the westward flowrate within this portion of the LWSC, potentially allowing the cooled water to move more quickly through the LWSC.

Two concepts for heat exchange were identified: one concept would withdraw and convey cold saltwater from the Puget Sound to a land-based heat exchanger, while a second concept would avoid withdrawal of the saltwater, instead pumping the freshwater through a radiator-like device (potentially many stacked loops in the pipe) on or near the bottom of Puget Sound intended to allow heat exchange with the adjacent saltwater. The land-based saltwater heat exchanger would require a marine intake, a large land-based heat exchanger, and a marine outfall to discharge the warmed saltwater. The marine intake would need to be far enough off the shore to access the deeper, cooler water of Puget Sound and minimize disturbance of the substrate below. The submerged heat exchanger concept would avoid challenges and concerns with new saltwater intakes and outfalls and would also reduce the real estate needs for the heat exchanger but would add the complication of a large, submerged pipe structure that would create a new concern with saltwater contamination and deep-water asset management and maintenance. Both options would increase construction and permitting complexity and significantly increase cost by requiring either an intake pipe or a looped pipe system to be installed in deep marine water, approximately 2 miles from the Locks, to access consistently cold water (to cool the LWSC water to around 15ºC, the cooling source must be below this 15ºC target). Both options would greatly increase head loss and required pumping energy due to the additional pipe lengths required. Figure 3-3 presents a preliminary sketch of the submerged heat exchange concept.

Water in Puget Sound is consistently 12ºC or less below 100 meters (Figure 3-4). Conceptually, therefore, an array of heat exchanger pipes would need to be placed in deep water. A rafted heat exchanger withdrawing from the bottom or a land-based heat exchangers may be possible but appears impractical in comparison to other cold-water sources such as hypolimnetic supplementation.

Review of NOAA bathymetry reveals that the closest point of 100 meters to the Locks lies approximately 2.0 miles off the Locks, 1.0-mile due west of the southern tip of the Shilshole Bay Marina breakwater. Without considering the heat exchanger itself or piping in the LWSC, approximately 4 miles of pumped conveyance would be required for the heat exchanger.

This distribution portion of the deep-water heat exchanger concept is somewhat like pumping water from Lake Washington: a large flow of cooled freshwater would spread laterally along density gradients throughout the LWSC. In this case, the concept would be a west to east piped flow, with the distribution piping extending the length of the LWSC. Whereas the westward flow of the LWSC may allow the Lake Washington hypolimnetic supplementation concept to pump flow for only a portion of the LWSC and to allow that cold water to be spread west by the 'natural' flow of the canal, the distribution system for the heat exchanger concept would need to extend the full length of the LWSC if cold water is to be provided for the full length of the LWSC.

The similarity between the concepts ends there, whereas cold water pumped from Lake Washington Is a low-head lift, friction losses through the heat exchanger and conveyance would be substantially higher, due to significantly longer lengths of pipe, requiring higher-pressure pumps and more pumping energy.

Most importantly, pumping of water would need to negate the heat gain in the hypolimnion of the LWSC; the warmest water from the west end of the LWSC would need to be cooled to below sublethal temperatures and returned east through the LWSC for distribution. Whereas the Lake Washington hypolimnetic supplementation concept would draw and distribute cold water, the heat exchange concept would start with warm water that has been warmed by the sun throughout the LWSC. Relatively simple calculations establish an order of magnitude of the required heat energy transfer. The pumping energy to move the same flowrate would have to be substantially greater than lifting water from the hypolimnion of Lake Washington to the LWSC because the heat exchanger would have to move water through a longer distribution network and work against the heat gain of LWSC hypolimnetic water, in part because the distribution system will be warmed by the warmer water in the LWSC itself.

Figure 3-3. Puget Sound Submerged Heat Exchange Concept

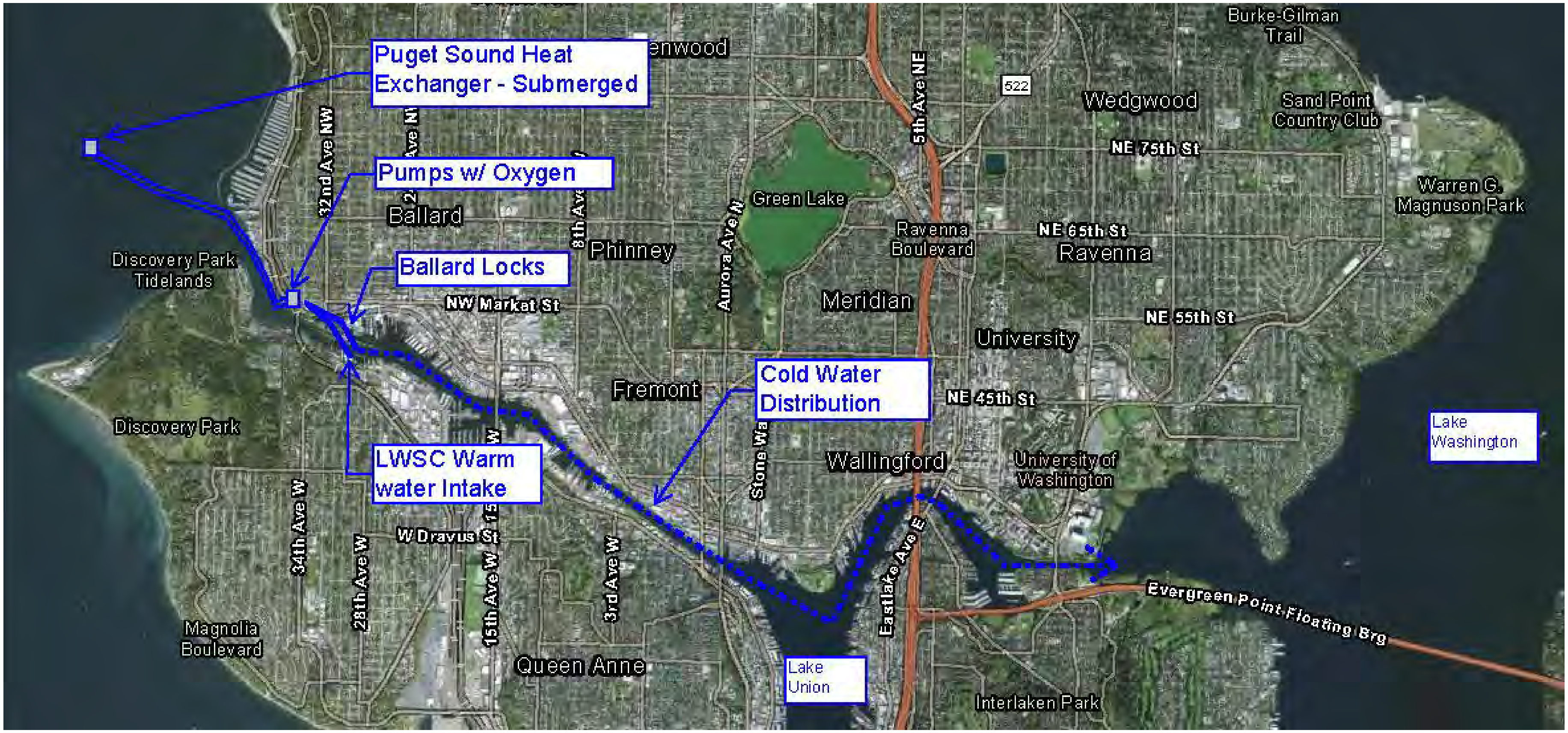
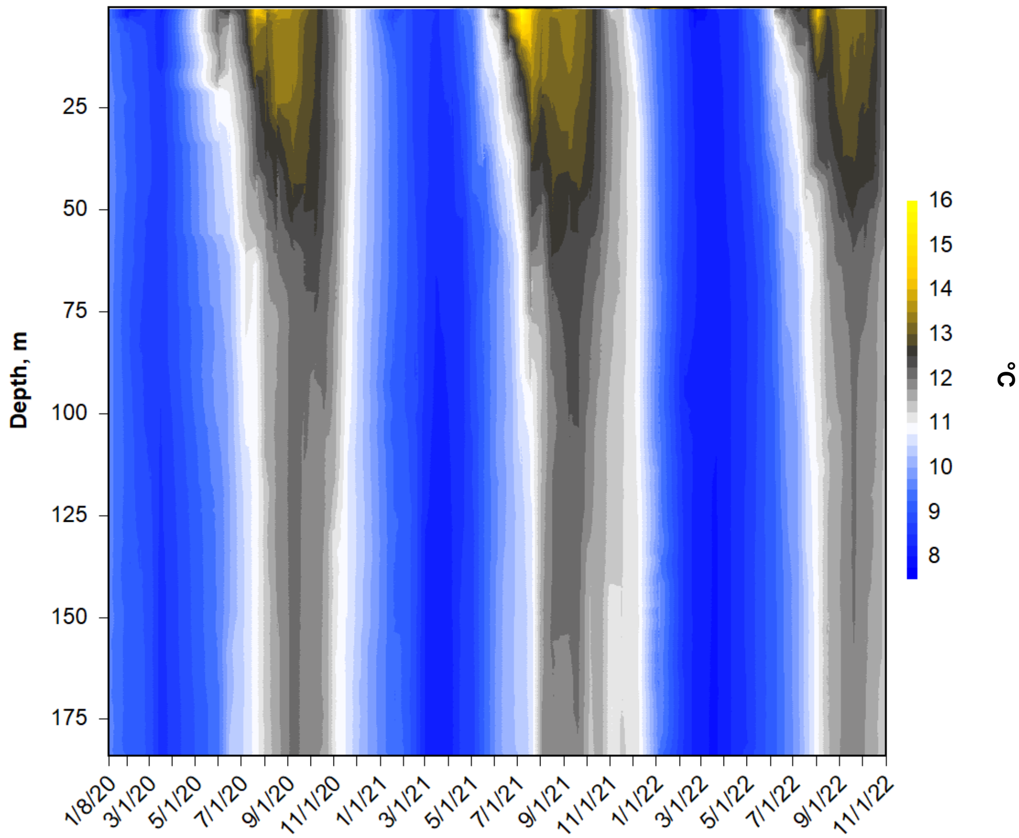


Figure 3-4. Puget Sound Temperature Isopleth at West Point Outfall (KSSK02)



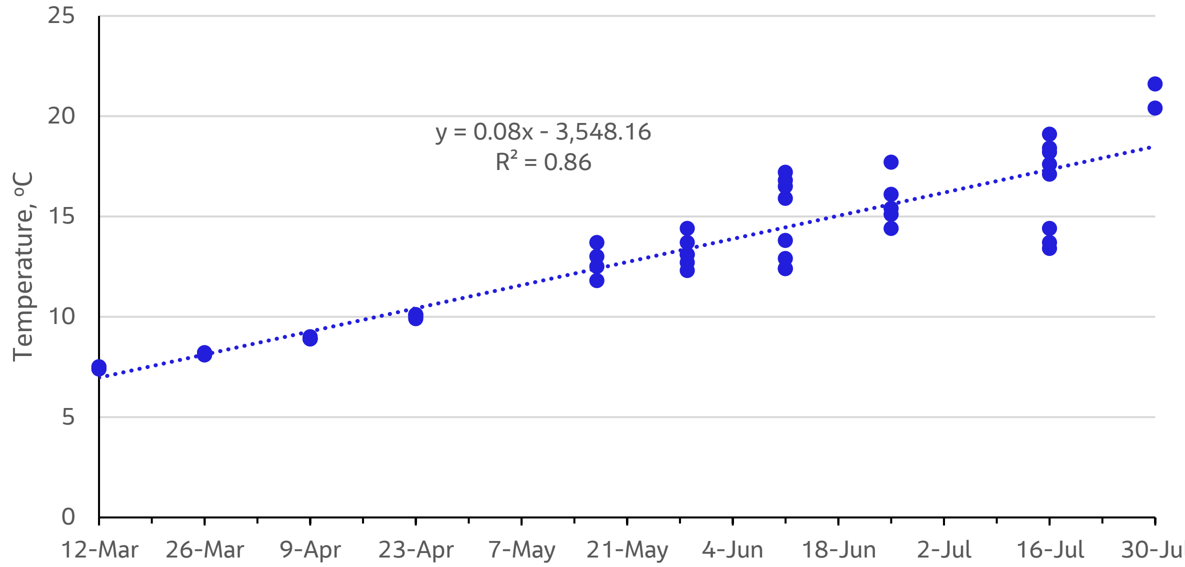
Notes:
°C = degrees Celsius
m = meter(s)

The hypolimnetic temperature gain in the LWSC canal, as measured in Lake Union (Station A522) is 0.08 degrees Celsius per day (°C/d) as measured in 2018 (Figure 3-5). A 1.0-meter-thick layer of cold water in the LWSC near 12 meters will have an approximate volume of 3,000,000 m^3. A heat exchanger would essentially have to remove heat from at least this water volume to prevent the heat gain of 0.08°C/d. A rough order of magnitude estimate of the minimum required capacity of the heat exchange system can be made from these observations.

The specific heat of water is 4,190 joules per kilogram °C. To prevent a heat gain of 0.08°C/d would require removing 335.2 joules per kilogram of water. In 3,000,000 m^3 of water a heat exchanger system would have to remove at least 1,000 gigajoules of heat per day simply to offset the solar gain in the LWSC, not including the need to offset the already-warm water from Lake Washington.

A heat exchanger of this capacity would be a very large, custom design and require deep marine construction to shed the heat unless combined with a district energy project. It is technically feasible, but likely a more complex engineering project than pumping cold water from Lake Washington. The relative proximity of the peak Puget Sound temperature in August (12°C) versus the desired cold-water temperature of less than 15°C limits the potential effectiveness of a simple potential heat exchanger. Obviously, if water in the LWSC was acceptable for salmon, it improves the feasibility of the alternative, but the additional obstacles in comparison to hypolimnetic supplementation still exist.

Figure 3-5. Hypolimnetic Temperature Gain in Lake Union (A255) at 8-Meter to 12-Meter Depth



Note:
°C = degrees Celsius

Pipe lengths of 2 miles or more in each direction would be required to and from the heat exchanger, greatly increasing both capital and operational (pumping) costs. In addition, if the water distributed within the LWSC must be approximately 10°C to provide a fish-passable region at 15°C or less, heat exchange [without a heat pump] would be impracticable due to the lack of temperature differential between the heat sink (Puget Sound) and the desired temperature of the cooled freshwater. It should be considered less practical as a stand-alone cold-water source and removed from consideration unless the Lake Washington hypolimnetic supplementation option proves to have unforeseen fatal flaws.

Heat exchanger calculations and preliminary design would be required to determine a feasible heat exchanger size and what amount of cooling could be provided via the Puget Sound heat exchanger concept; a modified LWSC temperature model including the associated distribution system [pumping east] would be required to determine what temperature reduction in the LWSC could be achieved with this system. Without a heat pump to shed additional heat, a larger flowrate and higher capacity (more or larger pipes or pumps) distribution system may be required to achieve the same temperature reduction as the Lake Washington hypolimnetic supplementation concept due to the cold-water source in Puget Sound not being as cold as the Lake Washington hypolimnion.

3.5 Heat Pump

If a heat exchanger placed in Puget Sound for cooling is not feasible, or does not provide sufficient cooling, a heat pump may provide an alternate source of cooling. The heat pump concept is anticipated to have the same distribution elements as the heat exchanger concept including withdrawal of (fresh) warm water from the east end of the LWSC and distribution through the LWSC toward Lake Washington.

A heat pump would most logically be located near the west end of the LWSC in order to reduce the length and pump energy require for the distribution system; for instance, water removed from the LWSC near the Locks, cooled in this vicinity and then pumped back to this vicinity would travel a relatively short distance, while water removed from the west end of the LWSC and pumped to a heat pump located at the east end of the LWSC would require all cooled water to be conveyed the length of the LWSC.

A heat pump would use electricity and a refrigeration cycle to reject thermal energy to cool the withdrawn freshwater in a land-based heat pump facility, potentially using deep wells to shed heat to the ground and groundwater below or rejecting heat to the sanitary sewer or a heat exchanger deep in Puget Sound. A ground-source heat pump system normally balances summer cooling with winter heating to avoid altering the long-term ground temperature increases and, therefore, losing efficiency; a stand-alone ground-source heat pump is infeasible in this instance due to the lack of balanced annual energy exchange and the large area required. The feasibility of a heat pump as a stand-alone cold water supply solution would be impacted by the high electricity need for the compression cycle, high anticipated land and capital costs, and the lack of hundreds of acres of space available for the well system. While a heat exchanger in large sanitary sewer transmission mains may provide an alternative to ground source wells, similar energy needs would be required due to the heat pump compression cycle, and installing large heat exchangers in the sewer would be expensive and challenging from both capital and O&M perspectives. However, district [Energy] heating is another type of potential land-based energy exchanger that could use heat pump chillers to remove heat from the LWSC to create warm water or steam for a campus or other district energy system. While not directly related to other cold-water sources discussed in this document, this could be a separate solution that might help the overall conditions in the LWSC. A district energy facility west of Lake Union could be of particular value, as the hypolimnetic supplementation from Lake Washington appears less effective west of Lake Union. Additional planning, coordination, and campus infrastructure improvements would be required to implement this solution. Energy savings on the ‘commercial’ side of this system would be needed to offset the high energy demand of the refrigeration cycle associated with the heat pump system.

Adding a heat pump and closed loop heat exchanger to the heat exchange concept may create sufficient temperature differential between the colder marine water and the closed loop portion of the heat pump to provide sufficient heat transfer. Considering the energy demand from the perspective of lowering the temperature of approximately 150 cfs by only 7°C (22°C to 15°C), the energy exchange required is approximately 35,000 tons of cooling, not including the energy for moving the water. This amount of cooling is approximately equivalent to cooling 13,000,000 square feet to 40,000,000 square feet of medium-use office space, depending on specific cooling demand, future summer temperatures, and other variable. A heat pump system would have high initial costs for the plant and associated energy use. A heat exchanger of this capacity would be a very large, custom design and would require significantly more energy than pumping water from Lake Washington. If less cooling was needed to benefit salmon, a smaller system may still provide a benefit.

Due to the high energy required and lack of an apparent feasible location for a land-based heat exchanger, the additional permitting complexities of placing either intakes and outfalls or a heat exchanger in Puget Sound, the multiple miles of additional pipe required, the relative inefficiency of pumping saltwater and/or freshwater so much further than the hypolimnetic supplementation option, the longer distribution system required within the LWSC, and potential infeasibility based on insufficient temperature differential [without large heat pump chillers], the heat exchange options are not recommended for further consideration at this time as a stand-alone system unless they can be paired with a district heating project or can be applied to a smaller portion of the LWSC such as at the Locks. A district heating solution could be suggested to other entities as having positive potential impact on the temperature of the LWSC, or a smaller version of this concept may provide cold water for a more focused area, such as the area immediately west of the Locks or the fish ladder. A fully commercialized district energy system that provided cold water to the LWSC and heat to others is likely subject to changing energy markets and the ability to secure and maintain users to make it economically feasible.

Similar to other cold-water options, a ground-source heat pump or even a heat pump shedding heat to a sewer interceptor may be feasible on a smaller scale to address a unique need such as cooling just east of the Locks. (Sewer heat exchange faces unique challenges including clogging from fat, oil, and grease in the sewer water, but is being developed [for heat extraction] in King County as a pilot and may ultimately offer a partial solution.) While likely not feasible at the scale needed to cool the majority of the LWSC, further coordination with King County WTD could be pursued to identify if a smaller solution is feasible.

A potential derivative of the heat pump option would be to locate the heat pump at the east end of the LWSC, withdraw warm water from the surface of Lake Washington (as opposed to from the cooler, deeper hypolimnion); the distribution system for this concept may then be similar to the Lake Washington hypolimnetic supplementation concept, but the flow of the warmer water that currently enters the LWSC would not be disrupted or displaced by colder water.

3.6 District Energy Project (Implementation Method for Lake Washington Hypolimnion Water Source)

The district energy project under discussion is not an alternate source of cold water but is a potential implementation method for the Lake Washington hypolimnetic supplementation concept or possibly other concepts. This specific iteration of the project would draw cold water from Lake Washington, provide cooling at the UW campus, and discharge warmed water (still at a temperature lower than LWSC water, but warmer than water from the Lake Washington hypolimnion) back to the LWSC. If combined with a cold-water supplementation project for LWSC, this cold-water source would also be from the Lake Washington hypolimnion, but would include routing a portion of the water through a system on or near the UW Seattle campus for a district energy project that would provide UW with cooling in the summer and heating in the winter. This solution may be like the basic Lake Washington hypolimnion supplementation concept for intake and distribution but will consider if facility type, size, and/or water quality are affected by the district energy proposal.

One advantage of combining a district energy project at the UW campus with cooling for the LWSC may be the potential for shared facilities, including intakes, pump stations, and distribution piping. Locating the pump station on UW property may eliminate the need for a barge, reduce navigational concerns, and reduces the challenge of providing O_2 and electricity to a barge.

In this scenario, distribution of cold water into the LWSC for the intended cooling function may be more complicated than required for the district energy project alone due to the cold-water supplementation project's goal to reduce mixing. While the district energy project may employ an outfall designed to encourage mixing to ensure compliance with water quality standards (Washington Administrative Code 173-201A), which include temperature, and prevent or minimize erosion, the cold-water project intended to benefit salmon migration must likely design a [longer] diffuser to limit dilution of the cold discharge in the receiving water to provide a cold-water refuge along the LWSC. This cold-water refuge is expected to concentrate the cold water along a nearly constant elevation and encourage laminar flow of the cold water along the LWSC where the fish travel (for example, near the bottom). Further consideration is required to confirm this deeper cold-water refuge will benefit out-migrating juveniles as well as incoming adults.

While the O_2 demand for this district energy option would be similar to the basic hypolimnion supplementation concept, further consideration would be required to determine if and where O_2 should be injected and how it would be dispersed in the pumped water; this may depend in part on whether the intended cold-water source is pumped and distributed separately from the temperature-conditioned water for the district energy facility, or if the water is shared or mixed.

3.6.1 Critical Remaining Issues or Questions

One additional issue that would require further exploration, via modeling, is how the higher combined flow of the cooling and district energy projects would affect the overall flow regime within the portions of the LWSC between the intake and outfall. Because smolt only migrate downstream (with the water flow), analysis is required to confirm that the flows within applicable portions of the LWSC continue in the westerly direction.

Further analysis is also required to confirm that the larger annual volume of water withdrawn from the Lake Washington hypolimnion would be acceptable. Note that a district energy system that withdrew heat from the LWSC for district heating [only] could offer more synergy with the needs of the LWSC, particularly west of Lake Union. This approach would require an activity with high heat demand near the LWSC during the summer months. Further analysis could also be performed to consider use of the now defunct salmon return pool (Salmon Homing Pond located near UW Fish Hatchery) as a location for discharge.

3.6.2 District Energy Concept Business Case

A district energy business case (review of business case for district energy combined with cold-water source) could potentially reduce total costs for the combined system making any of the cold-water sources more economical to the point where it may improve the feasibility of the alternative, but an analysis of that business case is outside of the scope of this effort.

3.7 Prevention of Eastward Flow of Cold Water

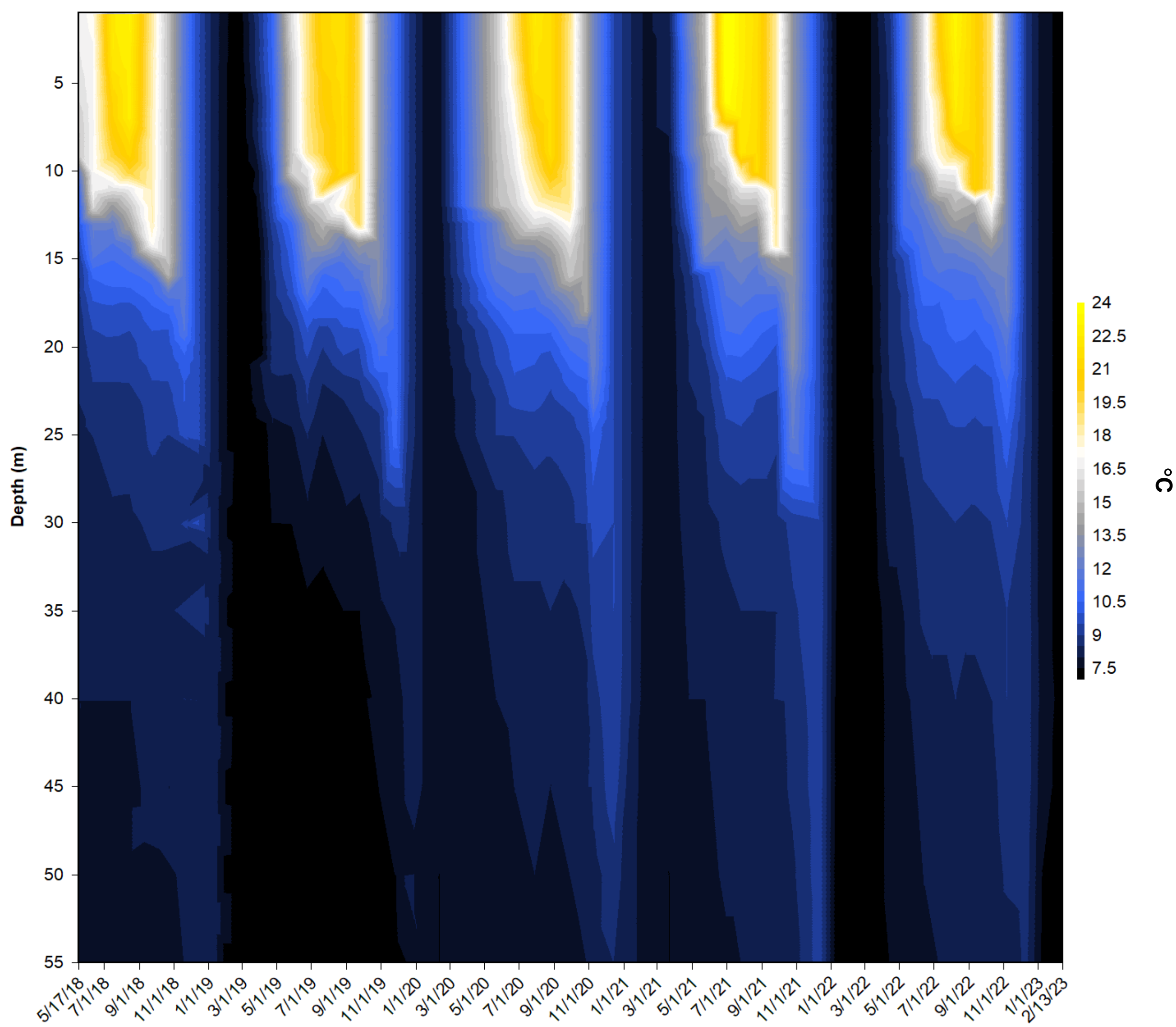
Upon consideration of first principles regarding water density and bathymetry, it is apparent that cold water discharged in or near the Montlake Cut near Union Bay would pour east through the dredged navigation channel into Lake Washington at Union Bay. The channel depth is approximately 7.5 meters. Lake Washington at the eastern edge of Union Bay is 47 meters deep. Cold water will move east out of the channel end to the depth of same temperature (Figure 3-6), which will be 20 meters or deeper. Thus, Lake Washington will be a cold-water sink for cold water pumped to the LWSC. Some kind of submerged density barrier may be beneficial on the eastern side of the LWSC to retain cold water in the LWSC and encourage cold water flow to the west. A similar barrier is currently used to control salinity inflow into the LWSC at the Locks. Further modeling is required to confirm the need and benefit of this facility, coordination is required to confirm this is feasible from a navigation perspective, and further analysis is necessary to review operational constraints.

To conceptualize cold-water flow, consider a single point inflow of cold water pumped from Lake Washington to the west side of the Montlake Cut. There will be a mound of cold water that will flow along the path of least resistance. Without a submerged density barrier, some cold water may flow east back to Lake Washington (Figure 3-7). With the density barrier, the cold water will flow west into the LWSC. Assuming a high enough pumping rate, the elevation of the cold water will reach the top of the barrier, or submersed weir in the barrier, and overflow into the Union Bay dredged channel and then into Lake Washington (while also flowing west toward Lake Union). The barrier would likely need to be inflatable and deflatable to allow deeper draft boats to pass. Lowering the barrier will sharply increase cold-water flows to Lake Washington. Hydrodynamic modeling is needed to characterize the issues and to determine an ideal barrier height. A dual density barrier operating in a manner somewhat analogous to a lock is a potential solution if analyses reveal excessive loss of pumped cold water to Lake Washington.

Note that this solution may be complex from an authorization, operation, and engineering standpoint. The purpose in identifying this issue and potential solution at this time is to articulate potential challenges and solutions that should be considered if and when this concept is advanced.

If possible, a single point of pumped inflow is preferred to facilitate construction, avoiding the complications of multiple points of inflow. Modeling will address this issue. Regardless, a density barrier should be considered as mandatory for planning purposes unless ruled out by hydrodynamics modeling. There may be a theoretical point at which an inflow pumping rate would be high enough to avoid problems with the cold-water loss to Lake Washington without the density barrier, but it is not yet known if that pump rate is practical compared to a pump rate supported by a density barrier or if this would create a condition with east-flowing cold water that may discourage smolt migration.

Figure 3-6. Temperature Isopleth of Lake Washington from WABUOY



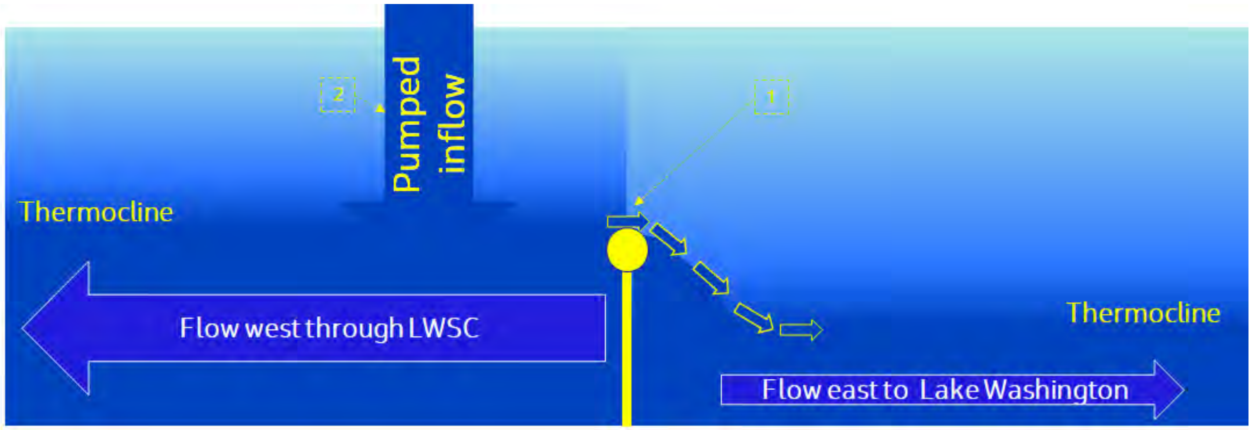
Source: King County (2016).

Notes:

℃ = degrees Celsius.

m = meter(s)

Figure 3-7. Conceptual Schematic of Cold-Water Flow at a Density Barrier



Note: No scale is provided on the figure.
Key:
1. Submerged, inflatable density barrier
2. Assumed pump inflow on the west side of the Montlake Cut

4. Lake Washington Hypolimnion Supplementation

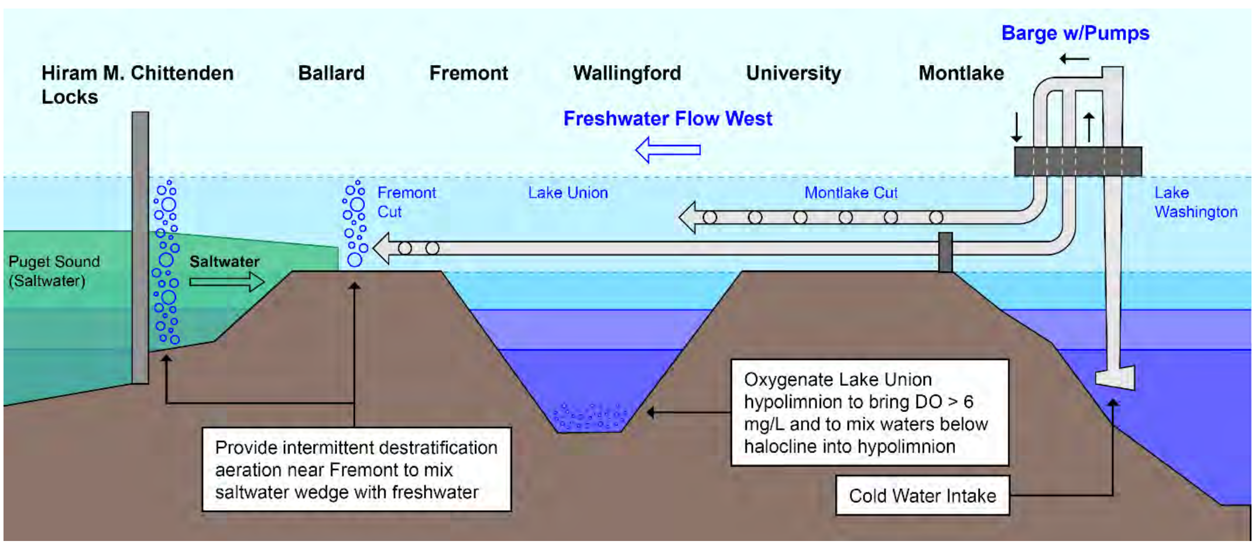
The Lake Washington hypolimnion supplementation concept was selected for further exploration and definition as a representative LWSC cold-water source. Modeling of the initial cold-water pumping rates and distribution system was performed to confirm the required flowrate(s) and identify conceptually what distribution system extents may be necessary. Initial model results were used to develop a short list of additional alternatives for further modeling and refinement; a final alternative was selected for further development including cost estimating. As previously stated, this is not a recommendation for this concept to be implemented without further refinement or analysis. The following section describes the refinements made to the initial concept, summarizes the modeling that was completed by others and examines the potential cost, schedule, permitting implications, and potential implementation strategies.

4.1 Concept Refinement

Initial modeling results for 125 cfs pumped discharged to the LWSC near Montlake suggested that this flowrate was insufficient to provide cooling, with little to no cooling benefit provided west of Lake Union. Further modeling and analysis suggested that a combined flow of 350 cfs, including 100 cfs distributed west of Lake Union, would provide measurable cooling throughout the majority of the LWSC, with the exception of the area immediate adjacent to the Locks.

The concept was refined to limit the pipe size to 48" outside diameter within the LWSC and 72" outside diameter from the pump station to Montlake. Figure 4-1 presents a schematic profile diagram of the Lake Washington hypolimnion supplementation concept.

Figure 4-1. Lake Washington Ship Canal Cold Water Supplementation Concept Profile



Note: Illustration above shows the potential concept to cool LWSC cold water pumped from Lake Washington hypolimnion. Destratification (bubble curtain) near locks and Fremont is to reduce saltwater migration, and oxygenation in Lake Union is to improve water quality. Drawing is not to scale. This is one concept to improve fish migration within the LWSC; further analysis is required to confirm feasibility.

4.2 Modeling

Modeling of the Lake Washington hypolimnion supplementation concept was performed by DSI, LLC in 2023. The initial modeling attempted to address several fundamental questions. The questions and corresponding answers are as follows:

- Will cold water pumped into a relatively short section of the LWSC near the Montlake Cut travel the full length of the LWSC, providing a continuous cold-water stream all the way to the Locks? Or is a longer, more distributed system required?

  Answer: No, the bathymetry of Lake Union and the salt wedge created by saltwater intrusion at the Locks limit cold water pumped near the Montlake Cut from traveling past Lake Union. [Note that further analysis is required to determine if destratification of the salt wedge west of Lake Union may render this single cold-water input concept more effective.]

- Will cold oxygenated water pumped into the bottom (or near the bottom) of the LWSC form a cold layer that does not mix, and is not excessively warmed by solar gain at the surface?

  Answer: Unknown. Preliminary modeling suggests that cold-water supplementation would form a cold-water layer at or near the bottom of the LWSC, but further modeling and/or field analysis is required to confirm the cold water will travel as far west as desired and will not be disrupted by propeller turbulence or other influences.

- Is the magnitude of the cooling effect limited by the distribution system (including constructability, navigation concerns), by the allowable flowrate, or by other factors such as solar gain?

  Answer: Unknown. This report presents one concept, including pipe sizes and cost estimates, that can be used to coordinate with agencies having jurisdiction to further explore limiting factors. Further analysis is required to determine if a larger system with more cooling effect is feasible, affordable, and beneficial, or if the maximum practical cooling effect is already represented and certain refinements are required to address feasibility. For example, if first cost or navigational concerns are limiting factors, could smaller distribution pipes with higher velocities increase feasibility or allow more cold-water distribution?

- Does Lake Union and the Fremont Cut west to the Locks require a separate or unique solution?

  Answer: Yes, a unique solution is required for Lake Union and also for the LWSC west of the Fremont Cut. And an additional solution may also be required near the Locks to address the tendency for salmon to congregate at and cycle through the Locks. The saltwater wedge may also restrict supplemented water from reaching the locks.

In summary, the model results do show potential benefit of the cold-water supplementation, but further advancement would be required to confirm feasibility and to consider the biological benefit versus the capital and operational cost. Refer to the DSI report for further detail.

4.3 Preliminary Cost Estimate

This preliminary (AACE International Class 5) cost estimate was developed to estimate the rough order of magnitude cost of the initial option. This planning-level estimate was created as an initial starting point from which to compare and contrast different options or suboptions (parts) and has an accuracy range of approximately -50 percent to +100 percent. The approximate range of the estimated cost is $477,000,000 to $954,000,000. Table 4-1 summarizes the preliminary cost estimate, and Appendix B provides further details.

Table 4-1. Preliminary Cost Estimate Summary

Part	Contents	Estimated Cost w/ Contingency
1	Permitting and Design	$22,000,000
2	200 cfs to Montlake and 50 cfs east of Montlake	$254,000,000
3	Additional 100 cfs to Fremont	$279,000,000
4	Oxygenation/Diffusion	$65,000,000
	Total Estimated Permitting, Design, and Capital Cost	$620,000,000
	Estimated Annual Operating Cost	$11,000,000

4.4 Permitting

4.4.1 Probable Regulatory and Permit Requirements

The following are regulatory and permit requirements that likely apply to this project:

- USACE Section 404 approval, likely the major environmental permit anticipated to be required for the project (further consideration is required to identify if this will be a Nationwide or Individual permit)
- **Section 7 Endangered Species Act consultation (formal)**, for construction; new structure potential for impacts on listed species also required through the Section 404 process
- **USACE Section 408 approval** for alterations or use of property federally authorized by the USACE
- **U.S. Coast Guard and/or USACE approval under Hazards to Navigation** (River and Harbor Act Sections 15-20)
- **WDFW Hydraulic Project Approval** for temporary and permanent in-water impacts
- **Construction Stormwater General Permit from Ecology** to treat and discharge construction water to adjacent freshwater
- **Permanent NPDES discharge permit from Ecolog**y for industrial facilities that discharge non-contact cooling water back into the river from which it was taken
- **Critical areas land use process with the City of Seattle Department of Construction Inspection (SDCI) and** construction permits from SDCI, SDOT (if new driveways or utility extensions in the right-of-way are required), and SCL for construction of new land-based facilities for power supply, oxygenation systems, or pumps (if land-based pumps are selected)
- **Local critical areas land use approval** for the in-water work
- **Coordination with the USACE and U.S. Coast Guard** for a barge vessel navigation
- **WDFW permits** for an over-water structure
- **Requirements for intake fish screens, pump energy, and distribution systems** for the Lake Washington hypolimnetic withdrawal would be similar regardless of pump station location
- **Coordination with the USACE, U.S. Coast Guard, WDFW, and other impacted parties** for feasibility and the permit pathway for locating a barge-based pump station in Lake Washington (or elsewhere)

- **Coordination with Washington State Department of Natural Resources (DNR)** to determine if the project is on or over state-owned aquatic lands and requires DNR Right of Entry or other permits

4.4.2 Estimated Permit Timeline

The single longest review is anticipated to be USACE review of the submittal application package for the Section 404 permit. Current typical permit review timelines for the USACE Section 404 permit are estimated to be at least 18 to 24 months.

While local (City of Seattle) building permits are not expected to be on the project's critical path schedule, critical area permitting could increase the length the overall project schedule; review process and timeline should be confirmed with SDCI if a refined alternative is selected to proceed toward permitting, design, and construction.

Depending on the specific location selected for pump station(s), extending SCL power may also require significant time, including SCL network engineering. Availability of sufficient network power should be considered in pump site location, and timeline required for SCL design and construction should also be confirmed when pump station location and power requirements are confirmed.

4.5 Implementation Strategies

The estimated cost of the cold-water supplementation strategy suggests that further analysis and refinement may be required to identify cost-effective solutions for cooling the LWSC. The cost and benefit of the individual parts of the concept as presented in the cost estimate could be considered separately to identify if portions of the overall concept are deemed to have sufficient benefit for advancement.

4.5.1 Individual Solutions for Advancement

While the broader cold-water supplementation concept is refined and outstanding questions are answered, components of the overall concept that could be considered for individual implementation include the following:

- Oxygenation of Lake Union
- Destratification (near Locks and in LWSC west of Fremont)

4.5.2 Public Outreach and Education

The LWSC, Lake Union, and the Ballard Locks are treasured by the people of Seattle and the broader region as beautiful places for recreation and commerce. Recent media coverage has identified the challenges that salmon face in traveling these waters, but further public education may be necessary to help the public understand the negative physical impacts warming water and low DO have on salmon. Development of graphics and educational materials to explain how construction of the Ballard Locks and rerouting of the Cedar and Black Rivers has negatively impacted salmon may be particularly informative. Proactive outreach will also be important to prevent any misconceptions about the project impact on water level, other uses of the water, environmental impact, or a number of other factors.

4.5.3 Funding Strategy

Navigating the numerous funding opportunities that exist to support water quality and temperature concerns critical to salmon recovery for a project of this size are included in this scope of work. For a significant project offering such large potential environmental impact as this one, using a comprehensive, long-term strategy combining low-interest loan financing, environmental impact bonds (EIBs), private equity, and federal and state grant funding as part of a laddering approach can be leveraged to provide large capital commitments up-front using innovative financing mechanisms, public private partnerships (P3s), heavily sculpted loan repayment terms, loan forgiveness, and grant funding resulting in significant cost savings and flexibility in eligible project activities. For example, both the Washington Clean Water State Revolving Fund Loan (CWSRF) and Water Infrastructure Finance and Innovation Act (WIFIA) loan programs provide financing for water quality projects that address habitat restoration, aquatic life, temperature total maximum daily loads, emerging contaminants, and variety of innovative engineering strategies using both gray and nature-based approaches. Each program guarantees below-market interest rates with up to 30-year repayment terms, potential loan forgiveness, and possible heavily sculpted repayment terms. These programs are a good companion since WIFIA can only provide up to 49 percent of the total project cost. The remaining 51 percent must come from other non-federal sources and the CWSRF program fills this cost-share requirement perfectly. Since they are both EPA financial assistance programs, their processes, terms, and requirements are mostly congruent, and they both recognize the validity and execution of over 11 different innovative financing mechanisms. This pairing maximizes flexibility and overall cost savings on leveraged funds.

The WIFIA has funded high-dollar projects to the tune of $1 billion and the program can support limitless financing structures. Some of these include Programmatic Financing, Master Agreement Portfolio Lending, Segment Cap Funding, and conduit lending approaches. Further, WIFIA offers a 5-year deferred repayment that allows the borrower to amass capital through the issuance of EIBs, donations, grant awards, or private equity so that cash reserves are robust when the first loan repayment comes due. By including a grant laddering approach and building a consistent application pipeline year after year, borrowers can increase their overall project cost savings by using these awards to pay down the debt service on WIFIA or CWSRF loans. What’s more, both the CWSRF and WIFIA program funds can be used to satisfy grant cost-share requirements. Used in conjunction, this can be a powerful strategy that supports a seamless, steady state of funding to keep the project continuously moving forward.

Another strategy may be to consider harnessing the power of a P3 to issue an EIB using the Quantified Ventures EIB Deal Kit that delivers step-by-step support and guidance through the issuance process, outcome quantification methodologies, template bond document environmental and social governance language, and verification as a Green Bond under International Capital Market Association Green Bond Principles, as well as United Nations Sustainable Development Goals alignment. This approach can attract long-term investors who prioritize environmental and social responsibility; thus, this increased investor interest can positively impact the issuer’s financial stability. EIB’s can help fill any funding gaps not covered by a WIFIA/CWSRF loan combo in a way that contributes to positive environmental outcomes but also offers financial advantages that are attractive to issuers and investors alike. King County, one of LLTK’s partners, has been actively involved in issuing Green Bonds as part of its commitment to environmental stewardship. Our Jacobs team has direct experience with helping clients with EIB issuances in Atlanta and Washington, DC.

To round out this approach, pursuit of suitable grant funding opportunities will help to drive down the overall cost of the project. The following outlines a suite of opportunities from the federal to boutique state grants that target salmon recovery in the Puget Sound region:

- USACE Continuing Authorities Program
- Of the nine legislative authorities that comprise the Continuing Authorities Program to plan, design, and execute specific types of water resource projects without requiring any additional congressional authorization, the best fit for this project is under Sections 107 and 206
- Section 107 – Small Navigation Project Study

- Improve navigation including dredging channels through a partnership with a non-federal government sponsor like a city, county, port authority, or unit of state government (UW).
- Maximum federal cost is $10 million
- Feasibility analysis is $100,000 with 50-percent cost-share
- Project cost: Non-Federal cost is 10 percent up-front during construction and 10 percent over a 30-year period for harbors with a design depth of 20 feet or less. For design depths of 20 to 45 feet the up-front share increases to 25 percent, and over 45 feet to 50 percent.
- Section 206 – Aquatic Ecosystem Restoration Projects.
- Focus on projects that restore aquatic ecosystems, fish, and wildlife and may include anadromous fish passage and dam removal, waterway restoration.
- Projects must be in the public interest, are cost effective, and limited to $10 million in Federal cost. USACE will provide the first $100,000 to cover analysis costs.
- A non-federal sponsor must contribute 50 percent of the feasibility analysis after the first $100,000, 35 percent of the design and construction cost, and 100 percent of the O&M costs.
- NOAA Fisheries Pacific Coastal Salmon Recovery Fund (PCSRF)
- While the PCSRF does not directly address temperature total maximum daily load projects in its overview of eligibilities, this program's comprehensive approach supports projects that will contribute to the overall health and resilience of salmon, benefitting water quality and ecosystem stability.
- Partnerships with tribal nations as a project that benefit populations that rely on tribal treaty fishing rights that include the development or project designs necessary for on-the-ground habitat improvement are eligible.
- Notice of funding opportunity typically announced in January of each fiscal year (FY).
- $106 million in funds available to award.
- US Department of Energy Grant Programs
- Advanced Research Projects Agency-Energy supports cutting-edge research and development in energy technologies that may be able to support the feasibility of the District Energy project.
- This could be supplemented via the CWSRF or EIBs.
- Congressionally Directed Spending
- Allows Washington Congressional Representatives to advocate for Congress to direct funding straight to key projects that aim to promote worthy investments to specific projects that will have a significant impact on local communities and address critical needs.
- Requires communication and outreach to state representatives and their staff.
- Our Jacobs Team has a dedicated Government Relations Liaison on Capitol Hill that can facilitate such requests.
- The Puget Sound National Estuary Program's Stormwater Resiliency Grants
  - A tract for $1 million in new funding that will become available in March 2024 to fund projects that explore new, innovative technologies and techniques for best management practice installations to implement stormwater best management practices that address water temperature, among other climate related issues like flooding and sea level rise. The application

window for FY24 funding has closed, but new funding opportunities for projects that address the health of the Puget Sound and its ecosystem will be available in FY25.

- These grants can be used for pilot projects.
- $250,000 is the maximum award.
- No match is required.
- It may be difficult to make stormwater connection on this project compared to competing projects.

- Streamflow Restoration Grants (Ecology)
  - New program provides funding for projects that improve streamflow and in-stream resources.
  - Priority is given to watershed with Endangered Species Act-listed species.
  - Eligible projects include altered water management or infrastructure, watershed function, riparian and fish habitat improvements, environmental monitoring, and feasibility studies.
  - Application deadline is February 29, 2024.
  - No maximum is required.
  - No match is required.
- Puget Sound Acquisition and Restoration Large Capital Project Grants
  - This is provided for restoration, acquisition, and planning projects leading to preliminary or final design (no construction). Implementation must begin during the 2025-2027 biennium.
  - The current grant round closes April 10, 2024.
  - No maximum is required.
  - No match is required.
- Salmon Recovery Grants through the Washington Recreation and Conservation Office
  - Funding is provided to improve habitat conditions or watershed processes to benefit salmon and bull trout.
- Washington Coast Restoration and Resiliency Initiative Grants
  - Funding is offered for community resiliency, restoration, and protection efforts supporting salmon recovery along Washington's coast.
  - Application deadline is May 2024.
  - $1 million is the maximum.
  - Fifty percent match is required.

5. Remaining Questions and Next Steps

We cannot say that this selected alternative is the most preferable as a full alternative analysis. Rather, this alternative represents the most feasible alternative based on assumptions contained in this report and serves as a potential starting point for additional discussion to understand the overarching considerations for cold-water supplementation. If this project is pursued, additional alternative analysis, as well as significant refinements and permutations of alternatives, will be needed to arrive at a final alternative.

5.1 Remaining Issues

The following issues are beyond the scope of the current investigation; these were not addressed with the current project scope and require separate consideration as alternatives are refined and modeling is advanced:

- Locks operation and creation of a more gradual temperature and salinity transition at the Locks requires additional discrete focus after biological criteria for this area are advanced.
- DO and other water quality parameters are not represented in the current model and will require separate consideration after a preferred water source and distribution system are identified.
- Review of proposed facilities is required with regard to navigation, both for the proposed pumping barge and for large pipes located within the LWSC.
- One or more submerged cold-water barriers may be required to prevent cold water pumped into the LWSC from flowing east toward Lake Washington. Further modeling and engineering would be required to confirm what cold-water barriers are required, and how these would be operated for ship navigation. Further analysis of the cold-water distribution system may identify a distribution concept that avoids the need for the submerged barrier, but the physical challenge created by Lake Washington bathymetry must be addressed.
- Smolt will not swim against the flow (will not swim upstream). Further modeling and consideration is required to determine if the overall flow regime in the LWSC or specifically the cold water flowing east in Union Bay will prohibit smolt outmigration.
- Regardless of cold-water source, some form of diffusion to limit mixing and dilution of the cold discharge in the receiving water is likely necessary to provide a cold-water refuge along the LWSC. Further modeling and subsequent design would be required to identify an acceptable diffusion system.
- Further coordination with King County Wastewater Treatment Division (WTD) would be required to identify if a heat exchanger shedding heat to the sewer would be helpful or allowable from a sewage collection and treatment perspective, and what amount of heat transfer may be feasible based on the flows adjacent to the LWSC.
- Review of nutrient flows and how nutrient flows may be affected by cold-water supplementation, if further action would be required to limit or offset increased nutrient flows or how the project could provide cobenefits to reduce nutrients.
- Confirmation of changes to the Lake Washington hypolimnion caused by cold-water pumping are acceptable from a biological perspective and can be accommodated by the proposed intake design.

5.2 Next Steps

Next steps for the project include the following:

- Review feasibility of and explore preference for barge-based versus land-based pump station.
- Characterize salmonid migration requirements for salinity, DO, and temperature at Locks.
- Determine the need for prevention of easterly plumped flows. If needed, provide conceptual design criteria and examples of similar structures to determine feasibility.
- Determine navigational constraints on pipe placement and diameter.
- Consider dredged options, with distribution pipes buried shallow through the Montlake cut and exposed in a dredged trench west of Montlake, may address concerns with both easterly pumped flow and with navigation. This combination of pumped cold water and shallower dredging may be more feasible and beneficial than past dredged options considered. Consider the options for and the benefits, impacts and feasibility of relatively shallow dredging combined with hypolimnetic supplementation from Lake Washington. Also consider if a dredged channel, beginning west of the Montlake Cut, would allow cold water to be pumped directly into the dredged channel, eliminating the need for expensive distribution piping. The *Lake Washington Ship Canal Water Quality Improvement Opportunities: Final Technical Review – August 2011* WSDOT 2011) provides dredging options that were considered infeasible.
- Consider the feasibility and benefit of a separate dredged option, between the Locks and Lake Union, to make room for additional flow of cold water east and provide room for submersed destratification systems to operate without interference of navigation. This concept may also increase the flow of saline water to Lake Union, potentially creating a layer of brackish water there in addition to a layer of cold freshwater in the LWSC. Further analysis would be required to determine both the feasibility of the dredging as well as the overall benefit to salmon migration.
- Refine hydrodynamic model to better characterize westward flow of hypolimnetic cold freshwater, underflow (below hypolimnion) eastward of denser, saline water, and flow of displaced epilimnetic water. The key issue is to better characterize the salinity “sill” that appears to block westward flow of pumped Lake Washington hypolimnion water.
- Determine need for diffusers of pumped Lake Washington hypolimnion water, perform value engineering exercise to review optimal balance of capital cost and operational efficiency (would shorter diffusers or smaller pipes be more cost-effective).
- Provide conceptual pilot design for hypolimnetic oxygenation of Lake Union: kilograms per day kg/d pure O_2, location of diffusers, length of diffusers, general specifications of diffusers. Next steps for oxygenation design include obtaining a second set of sediment characterizations for O_2 depletion rates (sediment chamber analysis). A more robust approach is to collect geochemical data (water samples), including dissolved metal quantities, to characterize how much O_2 is needed based on water chemistry in addition to the soil. Multiple measurements for the O_2 demand will increase the confidence in the design. A chemical baseline could be established now, and then additional measurements can be taken in the future to address interannual variability. Alternatively, a full-scale pilot could be implemented [potentially for one half of Lake Union] using the available data to test the O_2 demand, observe changes in the Lake Union halocline, and observe any changes to fish behavior. Note that sediment sampling should be performed when the DO is high, presumably in water or early spring.
- Provide conceptual pilot design for intermittent destratification aeration system near Locks to reduce density of salt wedge to less than the density of westward flowing pumped Lake Washington

hypolimnion water. A computational fluid dynamics model focused on the Locks area may be helpful for further this concept design.

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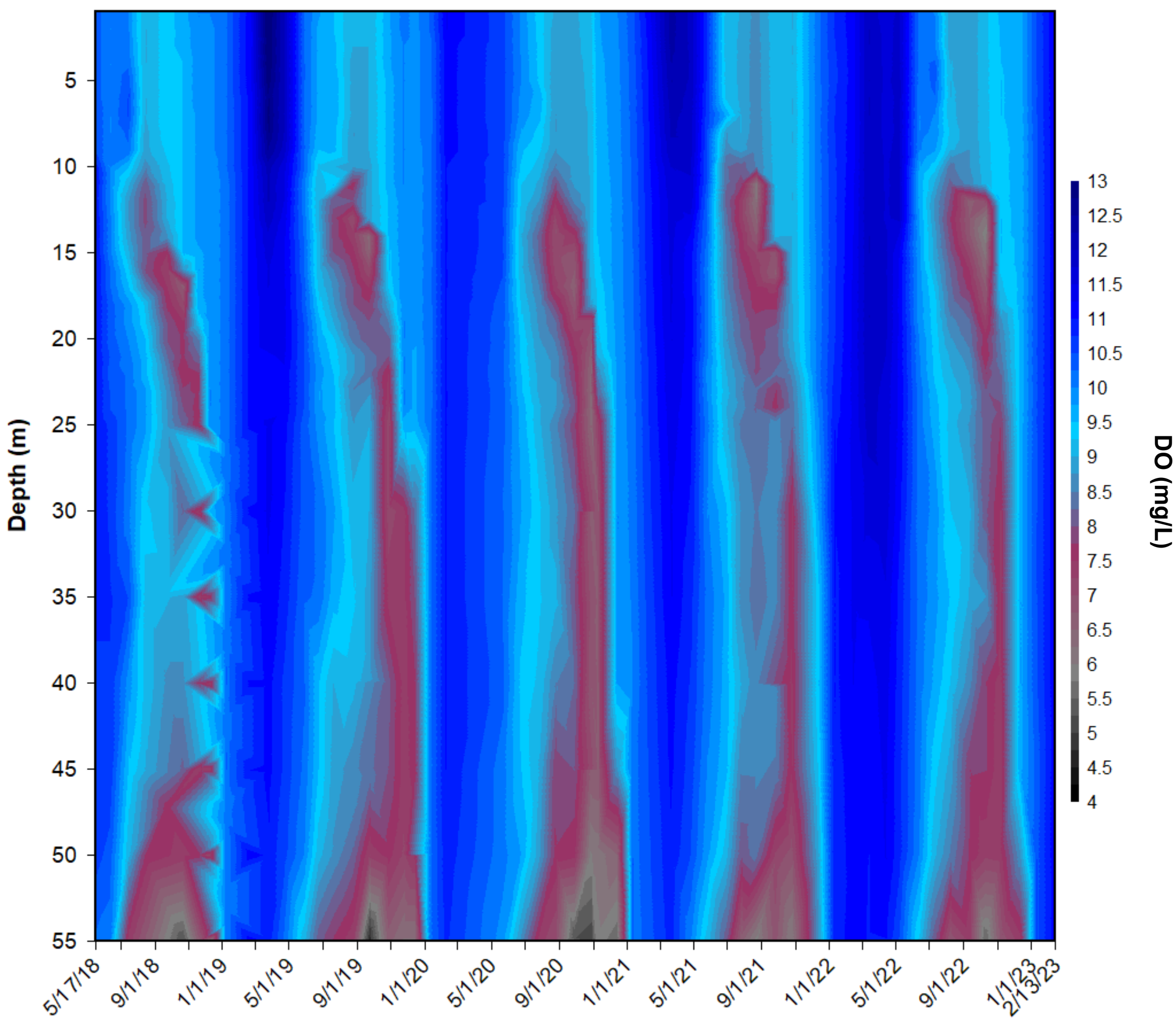
Appendix A
Dissolved Oxygen

Appendix A. Dissolved Oxygen

The proposed withdrawal location in Lake Washington balances temperature and dissolved oxygen (DO) (Figure A-1). Hypolimnetic DO falls below 8.0 milligrams per liter (mg/L) in the late summer most years. In 2018 through 2022 the lowest observed hypolimnetic DO was 4.0 mg/L at 56.1 meters. In the mid-hypolimnion (25 meters to 35 meters), the lowest observed DO was 6.5 mg/L. Thus, the mid-hypolimnion is a better water source than the deep hypolimnion because the DO is higher and no significant temperature advantage is associated with drawing water from the deepest areas of Lake Washington.

Figure A-1. Lake Washington Dissolved Oxygen Isopleth from WABUOY



Source: King County (2016).
Notes:
Blue shades represent DO higher than 8.0 mg/L acceptable for salmon.
DO = dissolved oxygen
m = meter(s)
mg/L = milligram(s) per liter

The target DO for the hypolimnion of Lake Union and the Lake Washington Ship Canal (LWSC) should be no less than 8 mg/L. Water pumped from Lake Washington will either not meet this criterion at the onset or will lose too much DO after in the LWSC or Lake Union. A preliminary intake depth from the surface of

25 meters to 35 meters (85 to 115 feet) appears ideal to balance temperature and DO. DO depletion of water pumped to the LWSC is a critical consideration. Water that meets DO habitat criteria when it is pumped in may not meet criteria within days or weeks.

Taking Lake Union as a depletion model, hypolimnetic DO in the LWSC will deplete from 6 mg/L to 2 mg/L from mid-May to mid-June, a period of about 60 days (King County and WRIA 8 Salmon Recovery Council 2021). The hypolimnetic oxygen demand (HOD) over this period is approximately 0.067 mg/L/d. Sediment oxygen demand (SOD) dominates HOD (Gantzer et al. 2019). Thus, water pumped into the LWSC and Lake Union will have approximately the same oxygen (O_2) depletion rate observed in situ.

At 9 degrees Celsius (°C), DO saturation in the hypolimnion is approximately 11.6 mg/L. A 3.6-mg/L DO loss would bring that water to the habitat DO threshold. At the observed HOD, that loss would occur in 54 days. However, the mean hypolimnetic DO May to October is 9.7 mg/L. The minimum DO is 4.0 mg/L. Approximately 10 percent of May to October DO concentrations are less than 8.0 mg/L.

Observed HOD in the LWSC and Lake Union make it all but certain that supplemental oxygenation of hypolimnetic water in Lake Washington or in the LWSC/Lake Union will be necessary. A future round of modeling is needed to capture DO dynamics of pumped water in the LWSC and Lake Union to determine the best engineering response. A sense of how oxygenation would work can be conceptualized by considering the path of water pumped in from a cold-water source.

Cold water pumped into the LWSC will sink or float to the same density water. If prevented by subsurface barriers from flowing back into Lake Washington, then cold water will disperse laterally along the bottom throughout the LWSC and Lake Union, forming a cold hypolimnion. It will float above brackish water. The density difference in water of 6°C is about the same as the density difference from 1 part per trillion salinity.

Density driven hydrodynamics of pumped inflows will profoundly influence DO dynamics because a greater volume of cold water will pool in Lake Union. Consequently, the Lake Union HOD will exert a dominant influence on the overall DO status of water pumped from Lake Washington.

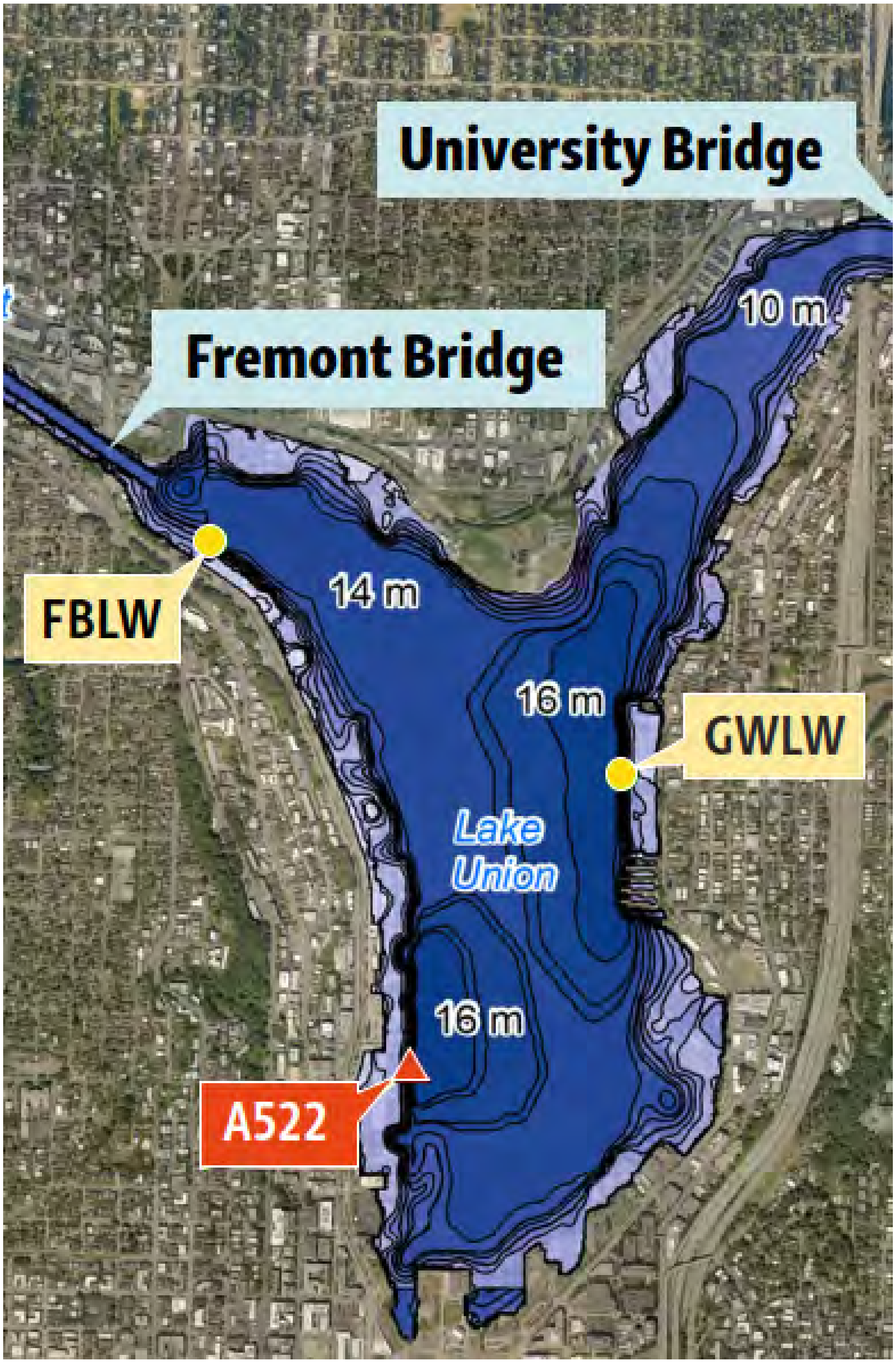
Conceptually, two choices for adding O_2 to the water are available: (1) add O_2 to the hypolimnion of Lake Washington, and (2) add O_2 to the hypolimnion of Lake Union. In either case, the means of adding O_2 would be linear diffusers sparging pure O_2 as is now widely used in drinking water and power reservoirs in the US (Mobley et al. 2019).

Because Lake Union will pool most of the cold-water inflow, special attention to Lake Union is needed for the overall scheme to ensure that it also meets DO habitat standards. Lake Union has two deep pools of 16 meters (Figure A-2). Sampling stations A522 and GWLW (Gas Works-Lake Washington) have profiles to a maximum depth of 14 meters to 15 meters.

The Lake Union thermocline depth during the stratification season is between 9 meters and 10 meters (Figure 2-1 in the Engineering Report). The thickness of the hypolimnion in Lake Union from the sediment surface to the top of the thermocline is approximately 6 meters to 7 meters. The hypolimnion is hypoxic (Figure 2-2 in the Engineering Report). Thermal stratification intensifies hypolimnion hypoxia, but hypolimnetic O_2 deficits can precede thermal stratification by about 60 days because of salinity stratification (Figure A-3).

The impact of Lake Union on the O_2 dynamics of cold-water inflow is apparent with simple calculations. The area under the hypolimnion is approximately 1,900,000 square meters (m^2). Assuming an average hypolimnetic thickness of 4.0 meters, the hypolimnetic volume is approximately 7,600,000 m^3. If water is pumped from the Lake Washington hypolimnion at a rate of 100 MGD (378,544 cubic meters per day [m^3/d]), the nominal residence time of cold-water inflows would be at least 20 days in Lake Union alone.

Figure A-2. Lake Union Bathymetry and Sampling Stations

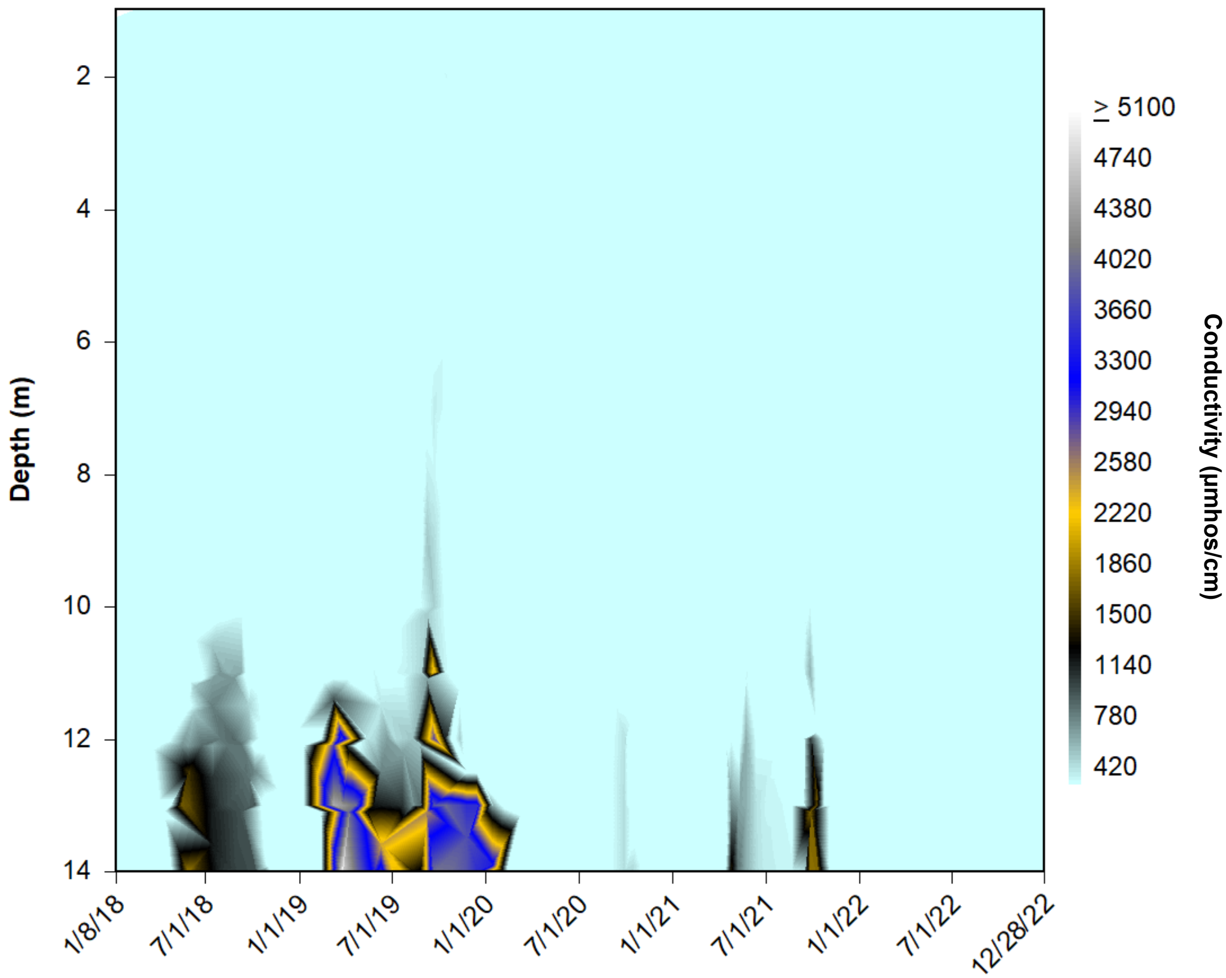


Source: King County and WRIA 8 Salmon Recovery Council (2021).

Notes:

FBLW = Fremont Bridge-Lake Washington
GWLW = Gas Works-Lake Washington
m = meter(s)

Figure A-3. Lake Union Conductivity

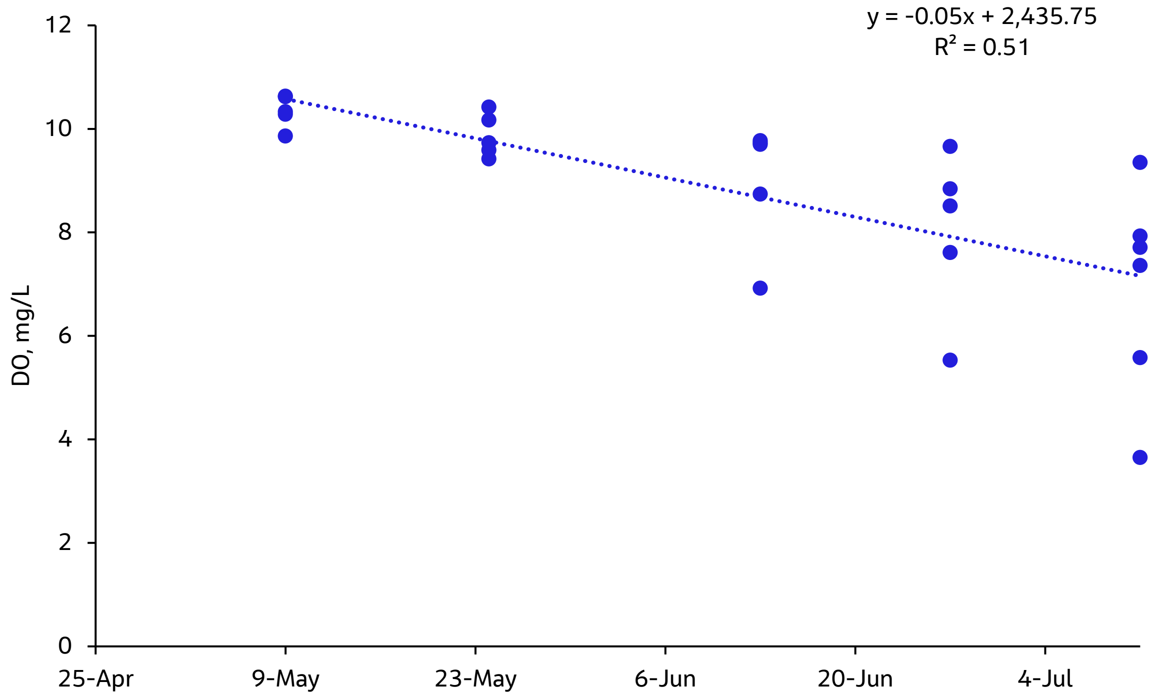


Notes:
Conductivity is provided in μmhos/cm.
≥ = more than or equal to
μmhos/cm = micromhos per centimeter
m = meter(s)

At the maximum observed specific HOD of 0.118 grams O_2 per m^3/d in 2018 through 2022 at 12.9-14.0 meters (Figure A-4), the DO loss over 20 days would 2.36 mg/L. A starting DO of 8.0 mg/L would fall below 6.0 mg/L. Moreover, the actual water age in the hypolimnion will likely be substantially larger because of small changes in salinity. In terms of water density, a 1.0 part per trillion salinity difference is approximately equivalent to a 6°C temperature difference. There will be an ongoing O_2 subsidy due to cold-water inflows that will require modeling attention. Regardless, it is clear the Lake Union hypolimnion will have an O_2-stripping function for cold-water inflows. Maintaining hypolimnetic DO over 8.0 mg/L below the thermocline in Lake Union and to the Locks is likely to require hypolimnetic oxygenation.

Assuming a hypolimnetic volume of 7,600,000 m^3, the total HOD is 932 kg/d. For planning purposes and redundancy, the conceptual design HOD would be 2.0 metric tons per day (tonnes/d) split between two diffusers, one at sampling station A522 and the other at GWLW. Both diffusers would rest on the bottom in the deepest area of these subbasins. Hypolimnetic oxygenation at similar depths in freshwater reservoirs have been operating successfully for over a decade (Austin et al. 2019; Mobley et al. 2019).

Figure A-4. Oxygen Depletion at Sampling Station A522 at 12.9-Meter to 14-Meter Depths



Notes:
DO = dissolved oxygen
mg/L = milligram(s) per liter

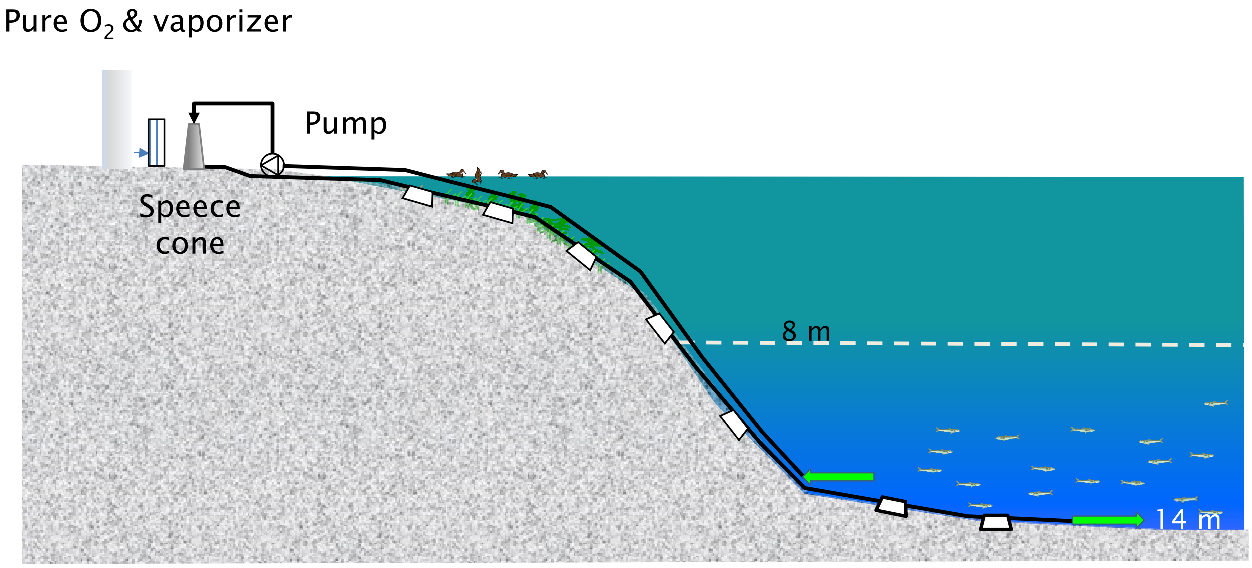
A key concept is that pure O_2, not aeration, would be used to maintain hypolimnetic DO over 8.0 mg/L. Hypolimnetic oxygenation preserves thermal stratification whereas aeration creates isothermal conditions that would create water conditions throughout the water column.

Two technologies are proven for hypolimnetic oxygenation: (1) sidestream super-oxygenation (Figure A-5) or (2) linear diffuser systems (Figure A-6). Design and choice of oxygenation for Lake Union are out of the scope of this report, but one or both technologies will be appropriate to the task of keeping hypolimnetic DO above 8.0 mg/L in Lake Union.

How much O_2 is needed in Lake Washington? Two ways for approaching this question are best: one simplistic and lakewide and the other closely tailored to water transfer.

The simplistic approach is to consider how much O_2 would be required to meet HOD throughout Lake Washington. Doing so would keep DO at saturation in the hypolimnion. The mean O_2 depletion rate in the mid-hypolimnion (25 meters to 35 meters) is 0.01664 grams m^3/d based on WABUOY data from 2018 through 2022. Applying that rate to the entire hypolimnion entails 30 metric tons O_2/d. To keep DO around 9 to 10 mg/L would be about 15 metric tons per day. Such an oxygenation system is well within the range of operating reservoir systems.

Figure A-5. Schematic of a Sidestream Super-Oxygenation Systems



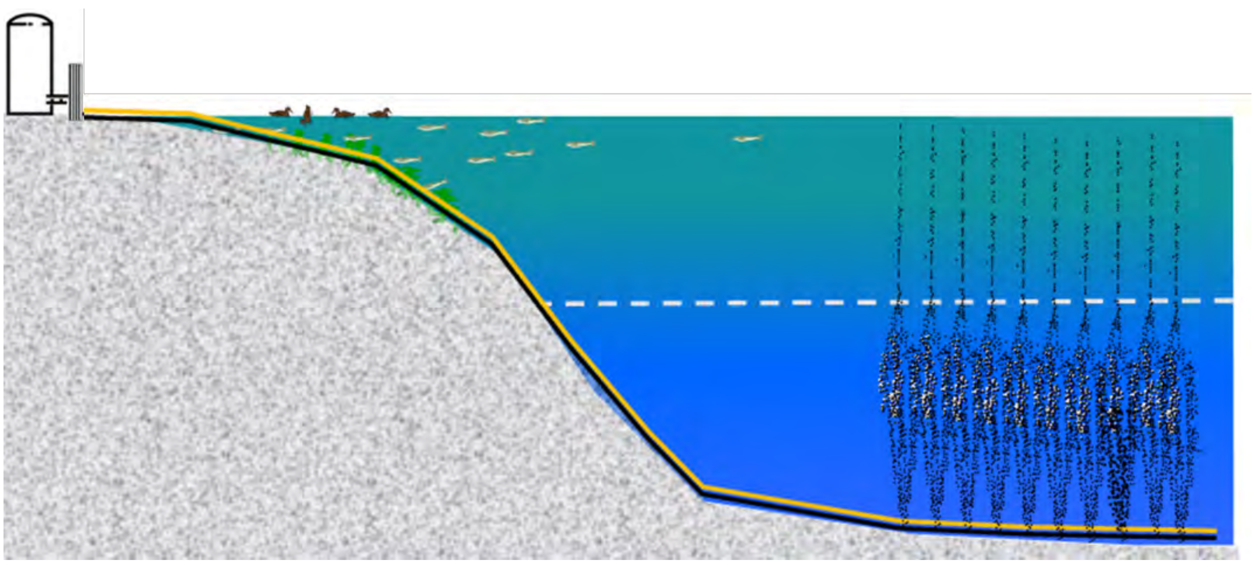
Notes:

Water pumped from the hypolimnion passes through a pure O_2 downflow contactor (Speece cone) and back to the hypolimnion. O_2 supply can be liquid O_2 or generated on site with a molecular sieve.

m = meter(s)

O_2 = oxygen

Figure A-6. Linear Diffuser System Schematic



Notes: The flux rate of pure O_2 through diffusers is engineered to ensure that O_2 bubbles dissolve into water before reaching the thermocline. Trace bubbles from the bubble plume have no lift and do not disrupt thermal stratification. LOX and vaporizer O_2 supply depicted.

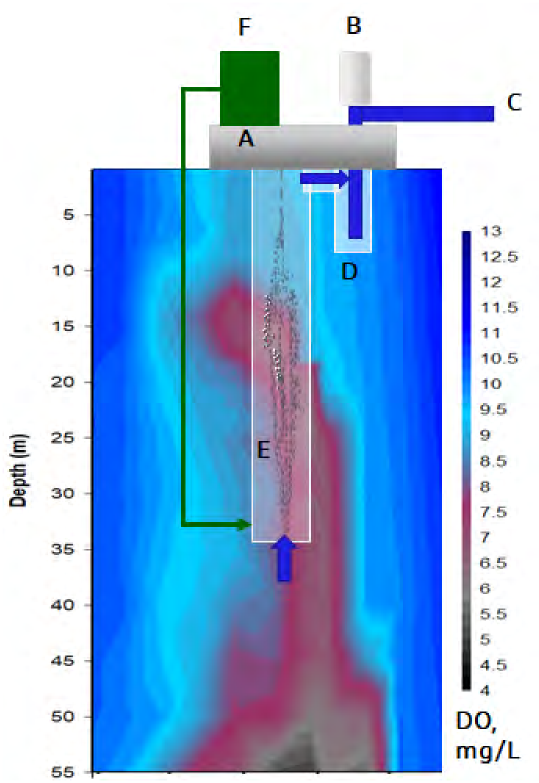
LOX = liquid oxygen

m = meter(s)

O_2 = oxygen

Focusing oxygenation on water pumped to the LWSC is most realistic. The concept is to pump from an oxygenated plume of water at the pump station (Figure A-7). For example, a 100 MGD (378,544 m^3/d) flow that requires a 4 mg/L boost to DO, would nominally require an additional 1,500 kg/d of O_2 from a diffuser set deep in a draft tube, probably near 30 meters deep. There would be a computational fluid dynamic modeling effort to design oxygenation of pump intake water. Regardless of the details, the O_2 demand of such a system would be an order of magnitude less than the lake-wide oxygenation approach. There are also other technically feasible means of adding dissolved O_2 to water pumped from Lake Washington. A side stream process utilizing a downflow pure O_2 contactor (Speece cone) could add 1.5 tonnes of dissolved O_2 to the pump discharge pipe at the pump station or at the cold-water outlet in the LWSC. Engineering opinion is that pure O_2 in a draft tube at the pump station is likely to be lower cost based on experience with lake and reservoir reclamation systems.

Figure A-7. Oxygenation Schematic for Lake Washington Pump Station



Note: A barge (A) supports a pump (B), sending water toward the LWSC (C) drawing water from a degassed pump well (D) supplied from a draft tube drawing water from the mid-hypolimnion into (E), which has pure O_2 is injected as supplied by a pressure-swing adsorption system (F).

O_2 generation will be required regardless of the cold-water source or pump station location or configuration.

Liquid O_2 (LOX) supply is not feasible for multiple reasons. A 9,000-gallon LOX tank would hold approximately a 30-day supply of O_2 for a 1 tonne/day system. Resupply by barge would be necessary, but barge supply of LOX is not an industry standard and is likely not feasible. The weight of the LOX alone would be 38,898 kilograms, and cargo capacity would be an issue of a barge for this weight. More importantly, stability would be an issue. LOX sloshing around the tank presents a classic stability problem in nautical architecture. Additionally, the issue of cryogenic safety on a barge likely would be difficult to overcome.

A pressure swing adsorption (PSA) generator can make 95-percent to 99-percent pure O_2 from air. A compressor pumps air into molecular sieves that adsorb nitrogen, allowing only O_2 to pass through to a pressure service tank. The molecular sieves are a zeolite media. When media are saturated with nitrogen, a purging step off-gasses nitrogen to the atmosphere to begin the next O_2 separation cycle. The electrical supply for the pump station would also supply compressors and the control system for the PSA.

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Appendix B
Preliminary Cost Estimate


(2) 2,000 LF
48" Diffuser
(2) 15,260 LF
48" Conveyance
to Fremont
(4) 2,000 LF
48" Diffuser
(2) 1,500 LF
48'' Conveyance
(2) 6,625 LF
72" Conveyance
(1) 4,710 LF 48"
Diffuser
(1) 630 LF 48"
Conveyance to
Union Bay
LWSC Pipes
Conveyance
Diffuser
0 1,000 2,000
Feet
Ship Canal Extent
LWSC Alternatives
LONG LIVE THE KINGS
Jacobs

LWSC Engineering Study

Task 5 - Preliminary Cost Estimates and Feasibility Considerations

Prepared: November 2023 Christi Gallo, John Nelson, Roger Shafe, Jesse Williams

Reviewed: Pat Burke

Class V Estimate for Seattle, WA

This preliminary estimate is based on a potential LWSC cold water supply concept for the purposes of cost estimating and further review and analysis. Significant physical, biological, ecological, cost, and other engineering factors require further study to confirm the feasibility of this concept. Other concepts may also be considered for improved cost efficiency or performance.

Part 1: Permitting and Design

	Item		Cost
1	10% Design and Permitting		$ 2,000,000
2	Final Design and Permitting		$ 10,000,000
3	Construction Administration and Monitoring		$ 5,075,000
	Subtotal:		$ 17,075,000
	Contingency:	30%	$ 5,122,500
	Total Part 1:		**$ 22,197,500**

Part 2: 200 cfs to Montlake and 50 cfs east of Montlake

Capital:

	Item	Description	Quantity	Unit	Unit Cost	Cost
1	Mob/Demob	Mobilization	1		20%	$ 22,700,000
2	Barge	9,000 SF Barge	1	each	$ 2,600,000	$ 2,600,000
3	Screen	50 cfs ISI Drum Screen	5	each	$ 696,000	$ 3,480,000
4	Pumps	50 cfs Vertical Turbine, 65 ft TDH	5	each	$ 1,320,000	$ 6,600,000
5	Shore Power - Property		1	LS	$ 5,000,000	$ 5,000,000
6	Shore Power - Development		1	LS	$ 20,800,000	$ 20,800,000
7	72" HDPE	Conveyance (solid) w/ anchors	6,625	LF	$ 3,900	$ 25,837,500
8	48" HDPE	Conveyance (solid) w/ anchors	3,630	LF	$ 2,700	$ 9,801,000
9	48" HDPE Diffuser	Diffuser pipe w/ holes and anchors West of Montlake - saddles and valves separate	8,000	LF	$ 2,700	$ 21,600,000
10	48" HDPE Diffuser	Diffuser pipe w/ holes and anchors East of Montlake - saddles and valves separate	4,710	LF	$ 2,700	$ 12,717,000
11	Diffuser Ports	Saddles with 6" Tideflex duckbill backflow preventers (west of Montlake)	1,200	each	$ 2,800	$ 3,360,000
12	Diffuser Ports	Saddles with 6" Tideflex duckbill backflow preventers (east of Montlake)	300	each	$ 2,800	$ 840,000
13	Subsurface Barrier	Operable subsurface barrier - TBD	1	each	$ 1,000,000	$ 1,000,000
	Subtotal:					$ 136,335,500
	Allowance for Indeterminates:		30%			$ 40,900,650
	Construction Subtotal:					$ 177,236,150
	State of WA Gross Receipts Tax:		10.1%			$ 17,900,851
	Contingency:		30%			$ 58,541,100
	Total Part 2:					**$ 253,678,101**

Part 3: Additional 100 cfs to Fremont

Capital:

	Item	Description	Quantity	Unit	Unit Cost	Cost
1	Mob/Demob	Mobilization	1		20%	$ 25,000,000
2	Barge	9,000 SF Barge	0	each		$ -
3	Screen	50 cfs ISI Drum Screen	2	each	$ 696,000	$ 1,392,000
4	Pumps	50 cfs Vertical Turbine, 65 ft TDH	2	each	$ 1,320,000	$ 2,640,000
5	Shore Power		0	LS	$ 10,000,000	$ -
6	72" HDPE	Conveyance (solid) w/ anchors	6,625	LF	$ 3,900	$ 25,837,500
7	48" HDPE	Conveyance (solid) w/ anchors	30,520	LF	$ 2,700	$ 82,404,000
8	48" HDPE Diffuser	Diffuser pipe w/ 6" holes and anchors - saddles and valves separate (west of Montlake)	4,000	LF	$ 2,700	$ 10,800,000
9	Diffuser Ports	Saddles with 6" Tideflex duckbill backflow preventers west of Fremont	600	each	$ 2,800	$ 1,680,000
10	Subsurface Barrier		0	each		$ -
	Subtotal:					$ 149,753,500
	Allowance for Indeterminates:		30%			$ 44,926,050
	Construction Subtotal:					$ 194,679,550
	State of WA Gross Receipts Tax:		10.1%			$ 19,662,635
	Contingency:		30%			$ 64,302,655
	Total Part 3:					**$ 278,644,840**

Additional cost to add cold water distribution west of Fremont after barge and pumps to Montlake are already in place.

Part 4: Oxygenation/Diffusion

Capital:

	Item	Description	Quantity	Unit	Unit Cost	Cost
1	Mobilization		1		20%	$ 5,800,000
2	PSA Oxygenation Station	Deep Lake Union Oxygenation	1	Each	$ 2,135,000	$ 2,135,000
2	PSA Oxygenation Station	Property Cost for Lake Union Oxygenation Station	1	LS	$ 4,457,000	$ 4,457,000
3	Destratification Aeration	Destratification (bubble curtain, etc.) west of Fremont Bridge	1	each	$ 1,863,000	$ 1,863,000
4	Destratification Aeration	Property for destratification west of Fremont Bridge	1	LS	$ 8,076,400	$ 8,076,400
5	Destratification Aeration	Destratification (bubble curtain, etc.) at/near Locks - intermitent operation	1	each	$ 1,863,000	$ 1,863,000

6	Destratification Aeration	Property for destratification at/near Locks	1	LS	$ 10,656,600	$ 10,656,600
	Subtotal:					$ 34,851,000
	Allowance for Indeterminates:		30%			$ 10,455,300
	Construction Subtotal					$ 45,306,300
	State of WA Gross Receipts Tax:		10.1%			$ 4,575,936
	Contingency:		30%			$ 14,964,671
	Total Part 4:					**$ 64,846,907**

Operating (Annual):

Item	Description	Quantity	Unit	Unit Cost	Cost
Annual Power Use for pump	East of Montlake: 1 Vertical Turbine pumps (50 cfs @ 21 ft TDH / pump)	1	Each	$ 88,485	$ 88,485
Annual Power Use for pump	West of Montlake: 4 Vertical Turbine pumps (50 cfs @ 29 ft TDH / pump)	4	Each	$ 122,194	$ 488,774
Annual Power Use for pump	East of Montlake: 1 Vertical Turbine pumps (50 cfs @ 39 ft TDH / pump)	2	Each	$ 164,329	$ 328,658
Cold Water Distribution Parts, Maintenance, and Replacement		1%	per annum	$ 5,971,698	$ 5,971,698
Cold Water Distributation M	1 FTE Staff	12	Month	$ 36,667	$ 440,000
Tender and Moorage		9	Month	$ 1,000	$ 9,000
Oxygenation Station	Maintenance and Probe Replacement	6	Month	$ 64,000	$ 384,000
Destratification Aeration	Maintenance and operation	12	Month	$ 52,000	$ 624,000
Subtotal:					$ 8,334,616
Contingency:		30%			$ 2,500,385
Estimated Annual Operation Cost:					**$ 10,835,001**

Not including insurance, management, permits

Total Capital Cost:	**Estimated Cost:**
Part 1: Permitting and Design	$ 22,000,000
Part 2: 200 cfs to Montlake and 50 cfs east of Montlake	$ 254,000,000
Part 3: 100 cfs to Fremont	$ 279,000,000
Part 4: Oxygenation/Diffusion	$ 65,000,000
Total:	**$ 620,000,000**

Total Capital Cost (Preferred Presentation as a cost range for Class V estimate):	
Total (without contingency):	**$ 477,000,000**
Total - Low Range (-50%)	**$ 239,000,000**
Total - High Range (+100%)	**$ 954,000,000**

Notes:

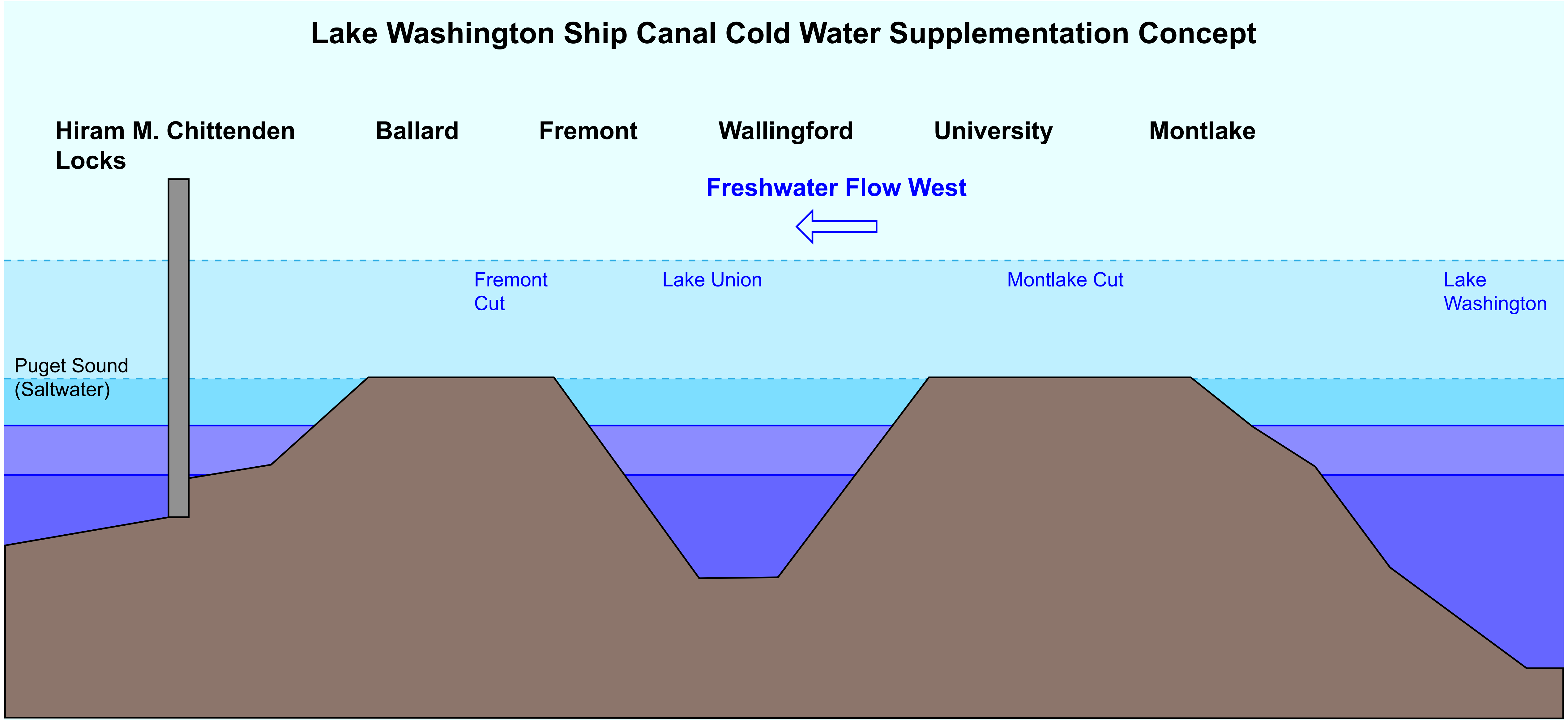
Escalation from 2023 costs is not included. Additional cost for prevailing wage may apply depending on funding source and implementing agency/entity.

Further study including modeling and review of potential navigation issues is required to confirm feasibility and performance requirements of pumped cold water diffusers; significant cost savings may be available if diffusers can be shortened and/or simplified.

The cost of extending cold water from Lake Washington to Fremont appears to be relatively expensive due to pipe length; an alternate such as a separate pump station from Lake Union may be a more cost effective solution to provide cool water in the LWSC west of Fremont. Further study is required to understand what combination of Locks operation changes, destratification, oxygenation of Lake Union, and cold water supply/pumping could most effectively cool this portion of the LWSC (west of Fremont).

Further study is also required to confirm the biological criteria for Locks operations and improvement, including what physical conditions would encourage salmon to 'move' east sooner. Oxygenation/destratification facilities are included as a preliminary concept for cost estimating, acknowledging that further study of this unique challenge is required. This appears to be relatively independent of the larger cold water supply concept.

Lake WA Cold Water Supplementation
LWSC Alternatives
0
2,500
5,000
Feet
LONG LIVE THE KINGS
Jacobs
Instructions: Open in a PDF viewing/ editing application. To turn a layer on or off, click on the layer name or symbol below. A red box will appear when the layer is on.
Important Landmarks
Basemap Labels and Roads:
Highway
Major Road
Bathymetry Contours (50 ft)
Bathymetry Countours (every 5 ft, less than 50 ft deep) in Ship Canal area
Water Depth (ft)
0
700
Lake WA & Puget Sound Surface Water
Subsurface Barrier
Oxygenation Points
Potential Destratification
Cold Water Distribution
Modeled Water Temperature (C) with Cold Water Supplementation
- click on bold layers below
Bottom Temperature-Click Here
Surface Temperature-Click Here
6-8.9
9-11.9
12-14.9
15-17.9
18-20.9
21-23.9
24-26.9
27-29.9
30-33
Cold Water to Montlake
72" Conveyance
48" Conveyance
48" Diffuser
Pump Station
Cold Water to Fremont
72" Conveyance
48" Diffuser
LWSC Pipe Labels
(2) 2,000 LF 48" Diffuser
(2) 15,275 LF 48" Conveyance to Fremont
(1) 6,850 LF 72" Conveyance to Fremont
(2) 6,625 LF 72" Conveyance to Montlake
Pump Station
(4) 2,000 LF 48" Diffuser
(1) 630 LF 48" Conveyance to Union Bay
(1) 4,710 LF 48" Diffuser
Puget Sound
NW 85th St
32nd Ave NW
15th Ave NW
8th Ave NW
Green Lake
Green Lake Park
Ravenna Boulevard
Ravenna Park
Sand Point Country Club
Warren G. Magnuson Park
Sand Point Way NE
Burke-Gilman Trail
522
99
Discovery Park Tidelands
NW Market St
Ballard Locks
Discovery Park
Ballard Bridge
Fremont Cut
Aurora Ave N
I5 Bridge
University of Washington
University of Washington Medical Center
Union Bay
Lake Washington
State Route 520
Fremont Bridge
Montlake Cut
Montlake Bridge
Lake Union
Magnolia Boulevard
Queen Anne Boulevard
15th Ave W
Interlaken Park
Eastlake Ave E
Centennial Park
1st Ave
Stewart St
2nd Ave
Madison St
Broadway
E Madison St
23rd Ave



Potential concept to cool LWSC cold water pumped from Lake Washington hypolimnion. Destratification (bubble curtain) near locks and Fremont to reduce saltwater migration, and oxygenation in Lake Union to improve water quality. Drawing not to scale. This is one concept to improve fish migration within the LWSC; further study is required to confirm feasibility.

Instructions: Open in PDF viewing application. To turn a layer on, click on the layer name below. Click on ☒ to turn a layer off

- Dissolved Oxygen
- Salt water interaction
- Pumping
- Sub-surface barrier
- Destratification

Note: Blue layers depict decreasing water temperature with increasing depth

Hydrodynamic Modeling Report

DSI LLC

LAKE WASHINGTON SHIP CANAL MODEL BASELINE MODELING REPORT AND EVALUATION OF COLD WATER SUPPLEMENTATION ALTERNATIVES

PREPARED FOR

LONG LIVE THE KINGS

SEPTEMBER 1, 2023

DSI LLC

Edmonds, WA USA

www.dsi.llc

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1 INTRODUCTION

The Lake Washington Ship Canal (LWSC; Figure 1.1) is a vital waterway connecting freshwater Lake Washington (Union Bay) to the saltwater Puget Sound (Shilshole Bay), via the Montlake Cut, Portage Bay, Lake Union, the Fremont Cut, Salmon Bay, and the Hiram M. Chittenden Locks. This engineering marvel, constructed in the early 1900s, supports the region's economic growth and recreational activities.

At the same time, however, the construction of the LWSC and Hiram M. Chittenden Locks (Ballard Locks) fundamentally altered the drainage pattern of the Lake Washington-Cedar-Sammamish watershed and created a pathway for seawater to intrude into the freshwater part of the system. Upon completion of the Ballard Locks, the level of Lake Washington dropped by approximately six feet from its historical water level, and the primary discharge point of the watershed shifted from the Green River-Duwamish River to the Ballard Locks through the LWSC. Consequently, the watershed's salmon, which are anadromous species, must migrate through the Ballard Locks via the fish ladder, smolt flumes, and large or small lock chambers.

Salmon are integral to the cultures, livelihoods, ecosystems, and tribal treaty rights of the Muckleshoot Indian Tribe and Suqamish Indian Tribe. Many salmon populations in the Lake Washington-Cedar-Sammamish watershed have declined in recent decades due to myriad factors. Key obstacles to salmon recovery in this watershed include lethal and sub-lethal high water temperatures and low dissolved oxygen (DO) concentrations in the LWSC during migration windows.

Water temperature is a primary determinant of salmon health, development, migration, and survival. Heat-stressed salmon face increased risks from parasites, infection, predation, and migration blockages or delays which can result in increased mortality rates and reduced spawning success (Urgenson, Kudo, and DeGasperi, 2021). Predatory fish species in the LWSC have a higher metabolism at warmer temperatures, allowing them to capture smolts more efficiently and digest them more quickly. Delayed migration due to high temperatures is of particular concern for juveniles that migrate through the LWSC and for adult Chinook and Coho Salmon, which will hold just upstream of the Ballard Locks instead of continuing upstream to reach the cooler waters of Lake Washington.

The study discussed in this report aims to evaluate the hypothesis that cold water supplementation to the LWSC can improve water quality for the benefit of juvenile and adult salmon by using an advanced mechanistic thermal and hydrodynamic model. The current study by DSI, LLC (DSI) consists of refining an existing 3-dimensional hydrodynamic model of Lake Washington, Lake

Union, and the LWSC previously developed by DSI to evaluate the effectiveness of this concept in reducing the potential for heat stress on migrating salmon. Several alternatives have been formulated through a collaborative effort among stakeholders. These alternatives focus on seeing the magnitude and extent of cooling that might be achievable through cold water supplementation in the LWSC by extracting water from the colder hypolimnion of Lake Washington and diffusing it into various locations in the ship canal to decrease the potential for highly stressful or lethal conditions for migrating salmon at different life stages.

Several temperature milestones have been established based on the Synthesis Report prepared by King County Water Resources Inventory Area 8 (WRIA8, which includes the Lake Washington-Cedar-Sammamish watershed) for the overall project (Urgenson, Kudo, and DeGasperi, 2021). Ideally, the outcome of the present study will be the development of one or more scenarios that are likely to produce consistent (*i.e.*, 95% of the time) temperatures localized to the bottom layer or through the water column below the following thresholds:

- Lethal Conditions per the King County Synthesis Report: 22° C
- Temperature Allowing Fish Passage Based on Tracking Data: 19° C
- Temperature Required for Salmonid Rearing and Migration Only: 17.5° C
- Core Temperature for Summer Salmonid Habitat: 16° C

Figure 1.1: Study area and locations for the Lake Washington Ship Canal.

1.1 Study Goals and Objectives

This study evaluates the potential for significantly reducing thermal barriers to fish passage in the LWSC through an extensive cold-water supplementation project. While largely hypothetical at this stage, this study intends to help further define the necessary scale of any future project(s) that may come about to meet these ambitious goals.

Through a collaboration with the organization Long Live the Kings (LLTK) and various stakeholders, DSI has conducted this preliminary environmental modeling study in response to the pressing need to understand and manage the environmental challenges associated with the LWSC as a pathway for salmon migration. The primary objective of this study is to assess the current conditions in the LWSC and to evaluate potential scenarios for reducing heat stress during the salmon migration season. By employing advanced modeling techniques, we simulate and assess the implications of these alternatives on temperature as a first proxy for the overall suitability of the LWSC for salmon habitat and passage.

This study seeks to provide insight into the complex interplay between natural processes and proposed anthropogenic intervention via cold water supplementation within the LWSC. By identifying and quantifying the potential impact of these actions, this study aims to inform decision-makers, policymakers, and stakeholders in implementing effective management strategies and help guide investment to provide a sustained pathway for salmon migration.

1.2 Report Organization

This technical report is organized into eight sections, each addressing a specific aspect of the LWSC environmental modeling study.

The first section (Section 2) documents the Modeling Framework for the study, where the overall hydrodynamic and temperature modeling framework is described. Specific attention is given to the simulation of stratified systems, as variations in temperature and salinity in the LWSC drive complex mixing processes, mainly due to the periodic formation of a salt wedge, which occurs because of saltwater exchange in the large lock chambers.

Section 3 (Data Compilation), Section 4 (Model Approach), and Section 5 (Model Development) delve into constructing the environmental model. This process encompasses the comprehensive data collection and compilation efforts undertaken to gather relevant information about the canal and a description of the model, emphasizing its suitability for simulating the complex dynamics of the LWSC. We outline the various components and parameters incorporated into the model, ensuring an accurate representation of the canal's physical processes.

Section 6 (Model Calibration and Validation) focuses on the crucial steps of fine-tuning the model to match real-world conditions and validating its accuracy. The calibration and validation process involves adjusting the model parameters to optimize the agreement between simulated and observed data from 2018 to 2021. We present the performance metrics employed for evaluation.

Section 7 (Scenario Development) explores different hypothetical scenarios to assess the potential impacts of three cold water supplementation plans on the LWSC. We describe the design and selection of representative scenarios provided by the Jacobs team. We outline the modifications made to the input data to simulate each scenario and present the simulation results obtained from the model.

In the subsequent section, Model Summary and Evaluation (Section 8), we compile and summarize the key findings from the scenario simulations. We compare the results of different scenarios against baseline conditions to identify and quantify the impacts of the three different cold water supplementation strategies on temperatures in the LWSC.

In the Conclusions section (Section 9), we summarize the entire study, reiterating the main findings and their significance in the context of the canal's environmental health. We provide recommendations for future changes to the model and input data, identifying potential areas of improvement and avenues for further investigation. We emphasize the importance of continued and extended monitoring and additional model enhancements to predict better the potential impacts of cold water supplementation on the LWSC.

The report is supported by a comprehensive list of References and two Appendices, which include the Quality Assurance Project Plan (Appendix D) and a section detailing comments received during stakeholder update meetings and associated responses (Appendix F).

2 MODEL FRAMEWORK, DESCRIPTION, AND FEATURES

The framework, description, and features of the model developed for this study are described below.

2.1 Model Framework

A three-dimensional hydrodynamic model was selected to simulate the hydrodynamics, temperature, and salinity conditions in Lake Washington and the LWSC. The Environmental Fluid Dynamics Code Plus (EFDC+) was selected to simulate hydrodynamics, water temperature, and salinity. The model formulation is based on sound science and peer-reviewed theory and application, as documented in the EFDC+ Theory Manual.[1] EFDC+ has become widely used in North America and Asia, and is available for free, including on-demand training,[2] community support,[3] and transparent, open-source code development through GitHub.[4]

2.2 Model Description and Features

Environmental Fluid Dynamics Code (EFDC) is a general-purpose hydrodynamic modeling package for simulating one, two or three-dimensional flow, transport, and biogeochemical process in surface water systems, including rivers, lakes, estuaries, reservoirs, wetlands, and near-shore to shelf scale coastal regions (Hamrick, 1992; Hamrick, 1996). DSI has further developed EFDC into EFDC+ to incorporate sediment/chemical fate, transport, and a coupled water quality model. EFDC+ Explorer, a Windows-based Graphical User Interface (GUI) developed by DSI, has been used for pre-and post-processing for the EFDC model. EFDC+ Explorer supports model set-up,

[1] https://www.eemodelingsystem.com/wp-content/Download/Documentation/EFDC_Theory_Document_Ver_11.pdf
[2] https://www.eemodelingsystem.com/video-lectures
[3] https://discourse.eemodelingsystem.com/
[4] https://github.com/dsi-llc/EFDCPlus

Cartesian and curvilinear grid generation, testing, calibration, and data visualization, including plots and animation of EFDC model results.

2.2.1 Simulation of Hydrodynamics in Stratified Systems

The fundamental principles of the hydrodynamic model in EFDC+ are the laws of conservation of mass, momentum, and energy based on the Reynolds-Averaged Navier-Stokes (RANS) equations. EFDC+ solves the RANS equations using a finite difference numerical method with a curvilinear orthogonal grid. The vertical structure of the water body was specified using a modified z-level coordinate system known as Sigma-Zed (SGZ; Craig et al., 2014). In general, z-level coordinates are more well-suited to simulate sharp density gradients and do not suffer from issues related to rapid change in bottom elevation, as seen along the deep portions of Lake Washington.

Hydrodynamic processes are described in terms of the mean flow conditions, and the effects of anisotropic turbulence are parameterized using an Algebraic Reynolds Stress Model (Canuto et al., 2001). Specifically, the momentum and energy budget is closed using a second-order k-ε model by coupling EFDC+ and the General Ocean Turbulence Model (GOTM; Umlauf and Burchard, 2003).

The EFDC+ model for LWSC incorporates density effects due to temperature and salinity. Transformation of the hydrostatic boundary layer for the RANS equations using the Boussinesq approximation for variable density results in the momentum, continuity, and transport equations for salinity and temperature in three coordinate dimensions (see Section 2.2.2). The density of water is provided as a function of temperature and salinity following the UNESCO equations of state (see Section 2.2.3), and buoyancy terms were computed in terms of the potential temperature (*i.e.*, the temperature of a parcel of water brought to a standard reference pressure adiabatically).

2.2.2 Basic Hydrodynamic Equations

The momentum equation in the x direction:

$$\begin{aligned}
&\frac{\partial}{\partial t}(m_x m_y H u)+\frac{\partial}{\partial x}(m_y H u u)+\frac{\partial}{\partial y}(m_x H v u)+\frac{\partial}{\partial z}(m_x m_y w u)\\
&-m_x m_y f H v-\left(v\frac{\partial m_y}{\partial x}-u\frac{\partial m_x}{\partial y}\right)Hv\\
=&-m_y H\frac{\partial}{\partial x}(g\zeta+p+P_{atm})-m_y\left(\frac{\partial h}{\partial x}-z\frac{\partial H}{\partial x}\right)\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left(\frac{m_y}{m_x}HA_H\frac{\partial u}{\partial x}\right)\\
&+\frac{\partial}{\partial y}\left(\frac{m_x}{m_y}HA_H\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{m_x m_y}{H}A_v\frac{\partial u}{\partial z}\right)-m_x m_y c_p D_p u\sqrt{u^2+v^2}+S_u
\end{aligned}\tag{2.1}$$

The momentum equation in the y direction:

$$\begin{aligned}
&\frac{\partial}{\partial t}(m_x m_y H v) + \frac{\partial}{\partial x}(m_y H u v) \\
&+ \frac{\partial}{\partial y}(m_x H v v) + \frac{\partial}{\partial z}(m_x m_y w v) + m_x m_y f H u + \left(v\frac{\partial m_y}{\partial x} - u\frac{\partial m_x}{\partial y}\right) H u \\
=& - m_x H \frac{\partial}{\partial y}(g\zeta + p + P_{atm}) - m_x \left(\frac{\partial h}{\partial y} - z\frac{\partial H}{\partial y}\right)\frac{\partial p}{\partial z} + \frac{\partial}{\partial x}\left(\frac{m_y}{m_x} H A_H \frac{\partial v}{\partial x}\right) \\
&+ \frac{\partial}{\partial y}\left(\frac{m_x}{m_y} H A_H \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{m_x m_y}{H} A_v \frac{\partial v}{\partial z}\right) - m_x m_y c_p D_p v\sqrt{u^2+v^2} + S_v
\end{aligned} \tag{2.2}$$

The momentum equation in the z direction:

$$\frac{\partial p}{\partial z} = -gH\frac{\rho - \rho_0}{\rho_0} = -gHb \tag{2.3}$$

The continuity equations (internal and external modes):

$$\frac{\partial}{\partial t}(m_x m_y \zeta) + \frac{\partial}{\partial x}(m_y H u) + \frac{\partial}{\partial y}(m_x H v) + \frac{\partial}{\partial z}(m_x m_y w) = S_h \tag{2.4}$$

$$\frac{\partial}{\partial t}(m_x m_y \zeta) + \frac{\partial}{\partial x}(m_y H U) + \frac{\partial}{\partial y}(m_x H V) = S_h \tag{2.5}$$

where U and V are the depth-integrated horizontal velocities,

$$U = \int_0^1 u dz, \quad V = \int_0^1 v dz \tag{2.6}$$

The equation of state for the density of water:

$$\rho = \rho\,(p, S, T, C) \tag{2.7}$$

The continuity equations for salinity S and temperature T:

$$\frac{\partial}{\partial t}(mHS) + \frac{\partial}{\partial x}(m_y H u S) + \frac{\partial}{\partial y}(m_x H v S) + \frac{\partial}{\partial z}(mwS) = \frac{\partial}{\partial z}(mH^{-1}A_b\frac{\partial}{\partial z}S) + Q_S \tag{2.8}$$

$$\frac{\partial}{\partial t}(mHT) + \frac{\partial}{\partial x}(m_y H u T) + \frac{\partial}{\partial y}(m_x H v T) + \frac{\partial}{\partial z}(mwT) = \frac{\partial}{\partial z}(mH^{-1}A_b\frac{\partial}{\partial z}T) + Q_T \tag{2.9}$$

and

u, v are the horizontal velocity components in the curvilinear coordinates (m/s),

x, y are the orthogonal curvilinear coordinates in the horizontal direction (m),

z is the sigma coordinate (dimensionless),

t is time (s),

m_x, m_y are the square roots of the diagonal components of the metric tensor (dimensionless),

m is the Jacobian of the metric tensor determinant (dimensionless), $m = m_x m_y$,

p is the physical pressure above the reference density hydrostatic pressure (m^2/s^2),

P_{atm} is the barotropic pressure normalized by the reference water density (m^2/s^2),

ρ_o is the reference water density (kg/m^3),

b is the buoyancy,

f is the Coriolis parameter (1/s),

A_H is the horizontal momentum and mass diffusivity (m^2/s),

A_v is the vertical turbulent eddy viscosity (m^2/s),

c_p is the vegetation resistance coefficient (dimensionless),

D_p is the projected vegetation area normal to the flow per unit horizontal area (dimensionless),

S_u, S_v are the source/sink terms for the horizontal momentum in the x and y directions, respectively (m^2/s^2),

S_h is the source/sink terms for the mass conservation equation (m^3/s),

S is salinity (ppt),

T is temperature (°C),

C is Total Suspended Solids (g/m^3), and

U, V are the depth averaged velocity components in the x and y directions, respectively (m/s).

The vertical velocity, with physical units, in the stretched, dimensionless vertical coordinate z is w and is related to the physical vertical velocity w^* by:

$$w = w^* - z\left(\frac{\partial \zeta}{\partial t} + \frac{u}{m_x}\frac{\partial \zeta}{\partial x} + \frac{v}{m_y}\frac{\partial \zeta}{\partial y}\right) + (1-z)\left(\frac{u}{m_x}\frac{\partial h}{\partial x} + \frac{v}{m_y}\frac{\partial h}{\partial y}\right) \tag{2.10}$$

where,

w is the vertical velocity component in σ-coordinate (m/s) and

w^* is the physical vertical velocity (m/s).

The pressure p is the physical pressure in excess of the reference density hydrostatic pressure, $\rho_o gH(1-z)$ divided by the reference density, ρ_o. In the momentum equations (2.1) and (2.2), the momentum source/sink terms S_u and S_v are later modeled as subgrid scale horizontal diffusion.

2.2.3 Equation of State

Water density is dependent on temperature and salinity, following UNESCO's equation of state for a parcel of water at reference pressure (*i.e.*, one atmosphere; UNESCO, 1981):

$$\begin{aligned}\rho =&999.842594+6.793952\times10^{-2}T-9.095290\times10^{-3}T^2\\&+1.001685\times10^{-4}T^3-1.120083\times10^{-6}T^4+6.536332\times10^{-9}T^5\\&+\Big(0.824493-4.0899\times10^{-3}T+7.6438\times10^{-5}T^2\\&\quad-8.2467\times10^{-7}T^3+5.3875\times10^{-9}T^4\Big)S\\&+\Big(-5.72466\times10^{-3}+1.0227\times10^{-4}T-1.6546\times10^{-6}T^2\Big)S^{1.5}+4.8314\times10^{-4}S^2\end{aligned} \tag{2.11}$$

where,

ρ is the water density (kg/m^3),

T is the water temperature (°C), and

S is the water salinity (ppt).

2.2.4 Simulation Efficiency

EFDC+ relies on OpenMP and MPI open-source technology to enable multi-threading and domain decomposition options for all simulations. DSI, 2020 showed that these upgrades to the EFDC+ framework supported more than 20 times faster model run times using more than 90 CPU cores. For the present study, domain decomposition of the model grid allowed the simulation to handle the ship canal and Lake Washington separately, which required communication between the domains for an extremely small number of cells. These features dramatically improve the model's ability to be applied to numerous scenarios promptly to help demonstrate a high likelihood of project success early in the feasibility evaluation process.

3 DATA COMPILATION

This section describes the available data sources for determining model inputs and calibration/validation.

3.1 Data for Building the EFDC Model

Table 3.1 lists the input data stations available for building the EFDC model.

Table 3.1: List of data stations available for the model build.

Boundary Name	**Measured Parameters**	**Time Period**	**Data Sources**
Sammamish River (51T)	Precipitation (inches); Stage (ft); Discharge (cfs); Water Temperature (°C)	1965-2023	`https://green2.kingcounty.gov`
KingCo34a	Stage(ft); Discharge(cfs); Water Temperature (°C)	1991-2023	`https://green2.kingcounty.gov`
KingCo35C	Air Temperature (°C); Stage (ft); Discharge (cfs); Water Temperature (°C)	1991-2023	`https://green2.kingcounty.gov`
KingCo37A	Stage (ft); Discharge (cfs); Water Temperature (°C)	1988-2023	`https://green2.kingcounty.gov`
27a	Air Temperature (°C); Stage (ft); Discharge (cfs); Water Temperature (°C)	1992-2023	`https://green2.kingcounty.gov`
58a	Air Temperature (°C); Stage (ft); Discharge (cfs); Water Temperature (°C)	2013-2023	`https://green2.kingcounty.gov`
12120000	Gage hight (ft); Discharge (cfs)	2007-2019	`https://nwis.waterdata.usgs.gov`
COB-06C	Stage (ft); Discharge (cfs); Water Temperature (°C)	2018-2023	`https://green2.kingcounty.gov`
Cedar River	Discharge (cfs); Water Temperature (°C)	2007-2023	`https://waterdata.usgs.gov`
Lake Wash Elev	Water Surface elevation (ft)	2001-2023	`https://www.nwd-wc.usace.army.mil`
Station ID: 9447130	Water Surface elevation (ft)	2010-2023	`https://tidesandcurrents.noaa.gov`
LWSC	Daily flow (cfs)	2001-2023	`https://www.nwd-wc.usace.army.mil`
Lake-Buoy	Relative Humidity (%); Solar Radiation (watts/sq meter); Atmosphere Pressure (mb); Wind Speed (m/sec); Wind Direction (degrees); Air Temperature (°C)	2008-2023	`https://green2.kingcounty.gov`
KSEA	Wind , Atmospheric data; Cloud Cover	2000-2023	`https://w1.weather.gov`

The list of stations above is used to create the input boundary for the model.

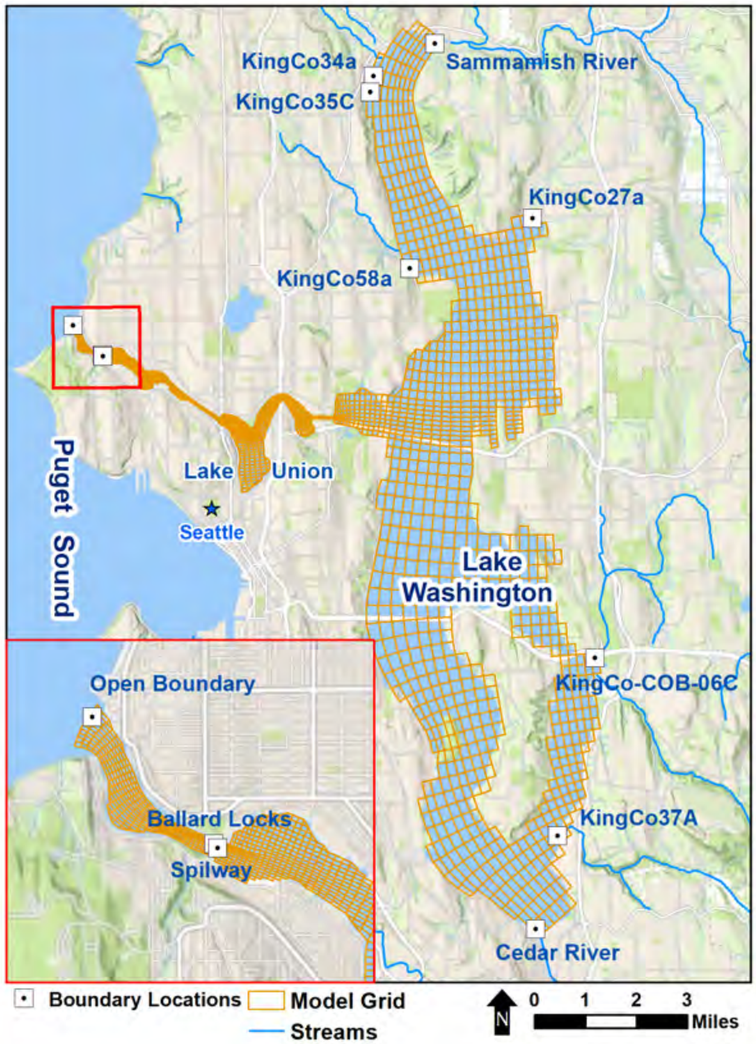

Figure 3.1: Model boundary locations.

Figure 3.1 shows the model boundary location based on the stations listed in Table 3.1.

The following statistical distribution can describe the total spillway flow based on data reported by the USACE between 2000 and 2023. The approximate residence time for Lake Union and Lake Washington based on each flow condition (assuming a constant flow) has also been provided below in Table 3.2. As can be seen from the approximate residence times, the waters of Lake Union are expected to have a residence time of just over one week on average, whereas Lake Washington's waters tend to have a residence time between 2 and 8 years (estimated from the interquartile range).

Table 3.2: Approximate distribution of discharge from the Ballard Locks spillway, based on USACE Data Query, LWSC Daily Flow 2000-Present

Spillway Flow		**Residence Time**	
		Lake Union	**Lake Washington**
	cfs	**Days**	**Years**
Minimum	43	235	74.85
1st Pct.	218	47	14.91
10th Pct.	261	39	12.46
25th Pct.	405	25	8.01
Median	754	14	4.31
Mean	1,254	8	2.59
75th Pct.	1,711	6	1.90
90th Pct.	2,747	4	1.18
99th Pct.	6,296	2	0.52
Maximum	13,381	1	0.24

In addition, DSI has investigated some meteorological and wind data that have the potential to provide usable data. Figure 3.2 shows the location of the meteorological stations, and Table 3.3 provides details of the parameters and the measurement time periods of these stations.

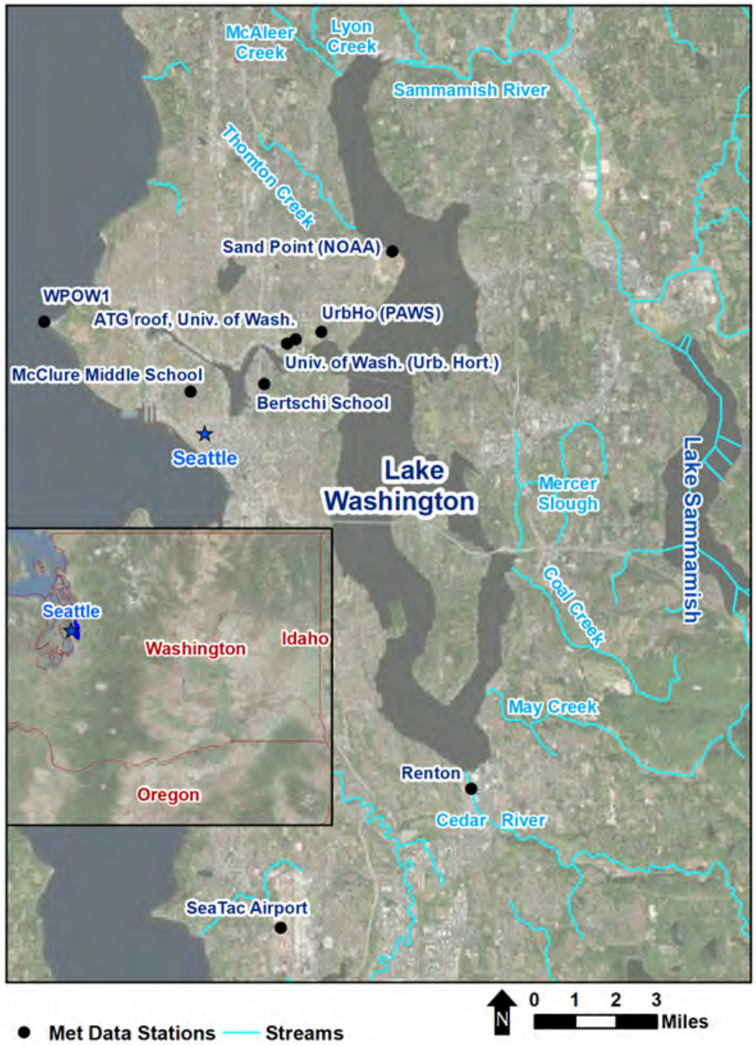

Figure 3.2: Meteorological and wind data stations.

Table 3.3: Meteorological and wind data locations.

Station Name	Measured Parameters	Time Period	Data Sources
SeaTac Airport	Temperature/Dewpoint (F) Relative Humidity (%) Wind speed/Peaks (knots) Wind direction (clockwise degrees from North) Sea level pressure (mb) Cumulative Rain (inches)	1996 -2023	`https://www-k12.atmos.washington.edu`
ATG roof, Univ. of Wash.	Temperature/Dewpoint (F) Relative Humidity (%) Wind speed/Peaks (knots) Wind direction (clockwise degrees from North) Sea level pressure (mb) Solar Radiation (W/m^2) [Bertschi/McClure/UW Only] Cumulative Rain (inches)	1999-2023	`https://www-k12.atmos.washington.edu`
Univ. of Wash. (Urb. Hort.)	Temperature/Dewpoint (F) Relative Humidity (%) Wind speed/Peaks (knots) Wind direction (clockwise degrees from North) Sea level pressure (mb) Solar Radiation (W/m^2) [Bertschi/McClure/UW Only] Cumulative Rain (inches)	2012-2023	`https://www-k12.atmos.washington.edu`
McClure Middle School	Temperature/Dewpoint (F) Relative Humidity (%) Wind speed/Peaks (knots) Wind direction (clockwise degrees from North) Sea level pressure (mb) Solar Radiation (W/m^2) [Bertschi/McClure/UW Only] Cumulative Rain (inches)	1999-2019	`https://www-k12.atmos.washington.edu`
Bertschi School	Temperature/Dewpoint (F) Relative Humidity (%) Wind speed/Peaks (knots) Wind direction (clockwise degrees from North) Sea level pressure (mb) Solar Radiation (W/m^2) [Bertschi/McClure/UW Only] Cumulative Rain (inches)	2007-2018	`https://www-k12.atmos.washington.edu`
Evergreen Point Bridge	Temperature/Dewpoint (F) Wind speed/Peaks (knots) Wind direction (clockwise degrees from North)	2011-2021	`https://www-k12.atmos.washington.edu`
UrbHo (PAWS)	Temperature/Dewpoint (F) Relative Humidity (%) Wind speed/Peaks (knots) Wind direction (clockwise degrees from North) Solar Radiation (W/m^2) [Bertschi/McClure/UW Only] Cumulative Rain (inches)"	2011-2022	`https://www-k12.atmos.washington.edu`
Sand Point (NOAA)	Temperature/Dewpoint (F) Wind speed/Peaks (knots) Wind direction (clockwise degrees from North)	2005-2014	`https://www-k12.atmos.washington.edu`
Renton	Temperature/Dewpoint (F) Relative Humidity (%) Wind speed/Peaks (knots) Wind direction (clockwise degrees from North) Sea level pressure (mb) Cumulative Rain (inches)	2001-2023	`https://www-k12.atmos.washington.edu`
WPOW1	Wind Direction (WDIR); Wind Speed (WSPD); Wind Gust (GST); Atmospheric Pressure (PRES); Significant wave height (meters); Dominant wave period (seconds); Average wave period (seconds); Sea level pressure (hPa); Air temperature (Celsius); Sea surface temperature (Celsius); Dewpoint temperature	1996-2021	`https://www.ndbc.noaa.gov`

3.1.1 Data on the Operation and Status of the Hiram M. Chittenden Locks and Dam

Cumulative daily and event-based data regarding the operation and conditions at the Hiram M. Chittenden Locks and Dam between 2015 and 2021 was obtained through a Freedom of Information Act request. These data include monitoring data, discharge data, operation codes, and water surface elevations.

These data were processed to provide the necessary boundary conditions to simulate the operation of the locks and dam explicitly so that the filling and emptying of lock chambers and the opening and closing of the lock gates could be included in the simulation.

3.1.1.1 Methodology for Determining Boundary Conditions

The US Army Corps of Engineers (USACE) provided several streams of data which reflect the operation of the Locks and Dam:

- Cumulative daily flow through different pathways, including the spillway, fish ladder, large lock, and small lock. Notably, however, the flow through the saltwater drain and the operational state were not included.
- Water level at the time of small lockage operations. However, the direction of the lockage was not included.
- Date, time, and operation code for the large locks. Each value represents an operation of the lower chamber (Code 1), upper chamber (Code 2), or full chamber (Code 3). Codes other than this were excluded, as their meaning was not known.

The USACE technical guidance regarding the construction and design of navigation locks, Davis, 1989, was consulted to help fill in gaps and provide mathematical approximations for the locks' operation based on these data.[5] Specifically, the design of the Ballard Locks follows the typical design for a large concrete navigation lock, with miter gates and a side culvert filling system designed for low-lift (under 30 feet) applications, as described by Davis, 1989.

Portions of design drawings for the Ballard Locks were obtained from the Master's thesis of Nielsen, 2011. Combined with widely-available images of the locks taken during repair and maintenance, and listed information, the following information for critical components of the design was specified as follows:

- Each culvert (*i.e.*, running parallel along the wing walls) for the large locks has cross-sectional dimensions of 8 by 14 feet, beginning upstream of the upper gate and ending downstream of the lower gate.
- A single-filling culvert exists for the small lock chamber, with a total cross-sectional area of 56.25 square feet. The small lock filling system appears to intake water from behind the small lock wing wall adjacent to the first spillway gate. The discharge appears to be behind the small lock wing wall, just downstream of the tailrace of the first spillway gate.

[5] Note critically that the Ballard Locks were designed and constructed almost a century before this guidance.

- The surface area of each lock was assumed constant: Small Lock, 30 feet wide by 150 feet long; Lower Chamber, 80 feet wide by 375 feet long; Upper Chamber, 80 feet wide by 450 feet long; Full Large Lock, 80 feet wide by 825 feet long.
- The head change required to fill or empty each chamber to equilibrium varies primarily with the tide level downstream of the Locks.
- The Large Lock chambers are located in sequence to one another, with the ability to operate as a complete, larger chamber or one smaller chamber.
- The Lower Chamber can only operate when the Upper Chamber is filled. Conversely, the Upper Chamber can only operate when the Lower Chamber is empty. Likewise, the Full Large Lock Chamber can only operate while both chambers are at the same level and the middle gate is open.
- As a first step, the typical filling rate for a lock chamber, given the approximate chamber volume, can be approximated by the relationship in Figure 3.3.
- For emptying rates, the problem is idealized as discharge under a falling head, using Pillsbury's equation (Davis, 1989):

$$t = \frac{2A_s}{C2A_c\sqrt{2g}}\left(\sqrt{H_1+d} - \sqrt{H_2+d}\right) \tag{3.1}$$

  where t is the time required for the lock to fill or empty from H_1 to H_2 after the valves are fully open, where $2A_c$ is the area of the culverts at the valves, and A_s is the area of the lock water surface. d is the lock overfill or underfill.
- Iteration of the filling or emptying time, and discharge rate, based on the initial head required for lock operation, was performed using several equations and relationships provided in Davis, 1989.
- Consistency between the lift head, chamber volume, discharge rate, and operation time was ensured using dimensional arguments.

Based on these assumptions, every required component of the lock operations can be described mathematically. However, the actual operation of the locks is not algorithmic, and delays are likely to occur due to safety or procedural reasons. However, at this stage of the process, several critical issues can be noted:

- In some cases, the time between lockage codes in the records provided by USACE was shorter than the typical filling or emptying time of the lock chamber and the estimated opening time (one minute for the small lock gate, two minutes for the large lock gate).
- Note that no consideration was made for the high variability of loading or unloading times for vessels from the chambers for the sake of simplicity. For example, consecutive Full Chamber lockage events might occur two minutes apart when the operations would be several times that duration.

- In such instances, if possible, the event was shifted in time to allow enough time for the operation before the next operation would proceed. Although in such cases, there would be almost no time for vessels to load into the chamber before the next lockage event.
- It is unclear if there is a typical resting state or the lock or if the chambers remain in their last used state.
- Many combinations of lock codes were inconsistent and would require lockages to be logical. For example, if a Lower Chamber and Upper Chamber event occur in sequence, then the only logical directions for each event would be a Lower Chamber down-lockage, followed by an Upper Chamber down-lockage.
- Likewise, several other likely sequences of up- and down-lockages can be inferred as likely. Several iterations, moving forward and backward through the time series, were required to arrive at the most logical overall sequence of operations to minimize the number of false lockages required to ensure that no illogical operations would be performed.
- False lockage events, or lockage events not recorded by the USACE, were occasionally required to continue the logical series of recorded events inferred in the previous steps. Iterations were performed until the smallest number of false lockages could be obtained, and those false lockage events were placed between events when required.

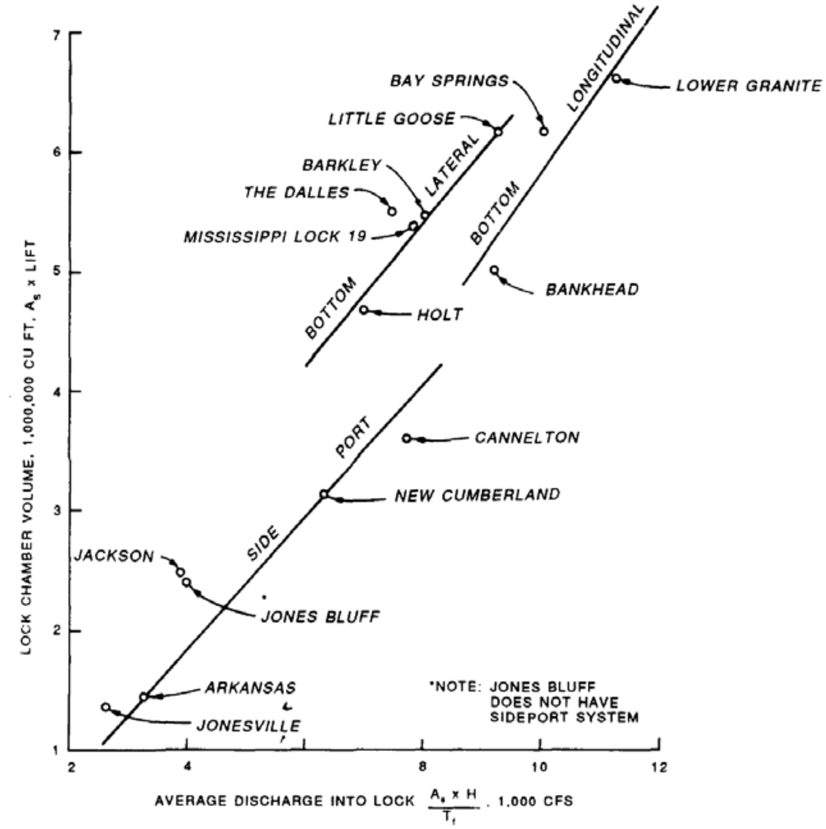

Figure 39. Lock volume versus average discharge (model filling time)

Figure 3.3: Typical Discharge for Filling Operations, as a function of Lock Chamber Volume.

3.1.2 Generation of Model Boundary Conditions for the Ballard Locks and Dam

Using the methodology described in the previous section, a complete time series of boundary conditions was used to formulate withdrawal and return boundary conditions for each filling and emptying operation. Based on the head maintained by the Dam, the flow direction is always from upstream to downstream in the culverts. Therefore, discrete time series needed to be generated for filling and emptying operations, with different return and withdrawal cells to represent the multi-port side culvert system.

For example, a single, large discharge and intake port is considered for the Large Lock, while filling and emptying the chambers is distributed between diffusers along the bottom of each chamber. Likewise, gate operations could only proceed for the lock chambers once the chamber levels reached equilibrium with the upstream or downstream elevation. Each sequence of operations for each lock element was appropriately synchronized to ensure stability in the simulation.

Each of these steps allowed the simulation to capture more realistic conditions related to saltwater lock exchange at these structures, which leads to saltwater infiltration to the freshwater Lake Washington Ship Canal during up-lockage events. The primary pathway is through the operation of the large lock due to its overall depth. A physical bottom barrier exists at the upstream end of the large lock to help block saltwater transport into the Ship Canal. There is also a saltwater drain on the upstream end of the Large Lock wing wall, but the operation of this element of the Locks and Dam is not documented.

3.2 Data for Calibration/Validation of the EFDC Model

Figure 3.4 shows the location of each station used for model calibration. Measured data for model calibration are listed in Table 3.4. These included primarily water level, water temperature, and salinity.

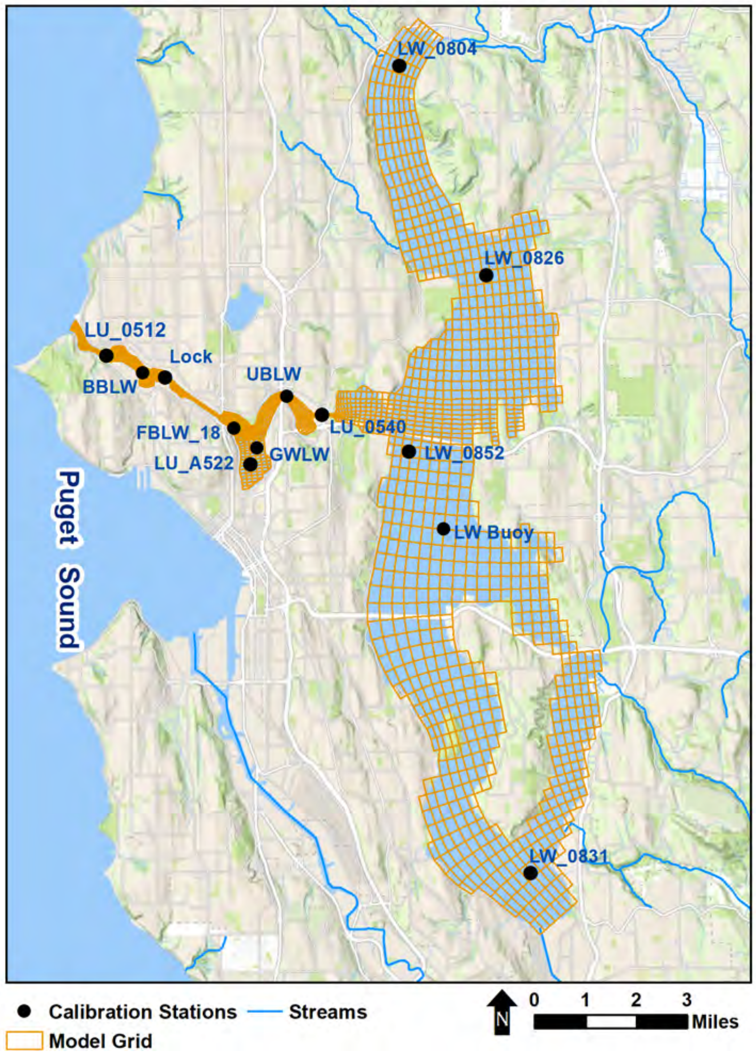

Figure 3.4: The DSI Lake Washington Model extended grid, with currently available calibration locations.

Table 3.4: Listed of data stations currently used for calibration/validation.

Station Name	Measured Parameters	Time Period	Data Sources
LU_0512	Water Temperature, Dissolved Oxygen; Conductivity, pH	1975 to 2022	https://green2.kingcounty.gov
LU_0540	Water Temperature, Dissolved Oxygen; Conductivity, pH	1975 to 2022	https://green2.kingcounty.gov
LU_A522	Water Temperature, Dissolved Oxygen; Conductivity, pH	1979 to 2022	https://green2.kingcounty.gov
LW_0890	Water Temperature, Dissolved Oxygen; Conductivity, pH	1995 to 2010	https://green2.kingcounty.gov
LW_0804	Water Temperature, Dissolved Oxygen; Conductivity, pH	1981 to 2022	https://green2.kingcounty.gov
LW_0826	Water Temperature, Dissolved Oxygen; Conductivity, pH	1982 to 2022	https://green2.kingcounty.gov
LW_0831	Water Temperature, Dissolved Oxygen; Conductivity, pH	1983 to 2022	https://green2.kingcounty.gov
LW_0852	Water Temperature, Dissolved Oxygen; Conductivity, pH	1993 to 2022	https://green2.kingcounty.gov
LW Buoy	Water Temperature, Dissolved Oxygen; Conductivity, pH, Chlorophyll-a	2008-2023	https://green2.kingcounty.gov
BBLW	Water Temperature, Salinity	1992-2022	https://www.nwd-wc.usace.army.mil
FBLW	Water Temperature, Salinity	1992-2022	https://www.nwd-wc.usace.army.mil
GWLW	Water Temperature, Salinity	1992-2022	https://www.nwd-wc.usace.army.mil
UBLW	Water Temperature, Salinity	1992-2022	https://www.nwd-wc.usace.army.mil
Lake Wash Elev	Water Surface elevation	2001-2023	https://www.nwd-wc.usace.army.mil

3.3 Data Acceptance Criteria

The primary data sources for this study are listed in Sections 3.1 and 3.2. In the course of model development, additional data sources may be identified. For data from external sources, assessment of data for acceptance for use as model input and calibration will follow these steps:

1. The data source must be investigated for documented data quality procedures.
    - Primary external data sources for model development, calibration, and validation include King County, the US Army Corps of Engineers, the National Oceanic and Atmospheric Administration, and the United States Geological Survey. These entities can be deemed highly reliable and responsive based on shareholder interest, sources of funding for data collection, and data quality standards. Detailed data descriptions and collection methods are readily available in the public domain for these sources.
2. Any qualifications or other metadata provided with the data set will be documented and evaluated.
    - Each entity collecting these data is a local or federal agency, and all documentation and metadata sources are readily available.
3. The data intended for use will be evaluated for outliers or unusual trends that may suggest data quality problems. Based on the evaluation of the data, which would include an investigation of unusual environmental or logistical conditions at the time of data collection, suspect data may be censored, qualified, or accepted.
    - In addition to DSI's standards of practice for inspection and quality assurance for model inputs, all model input files are automatically checked for errors, discontinuities, and completeness by DSI's EFDC+ Explorer software before running. In some cases, the government agency responsible for data collection may perform various levels of data quality assurance and control, and these processes are generally well documented. That said, erroneous data can sometimes remain or be subject to only preliminary approval from the collecting agency. Standard procedures for data inspection include generating statistics, plots, and comparisons to other reliable data sources when possible to thoroughly screen any data considered for model development, calibration, or validation.

3.4 Data Management

The final version of the model, including input, output, and software executable files, will be maintained for archiving after the project. Electronic copies of the data, GIS, and other supporting documentation (including records documenting model development) will be saved and stored as appropriate for agency policies on records retention practices. Copies will be maintained in a task subdirectory, subject to regular system backups, and on disk, for three years after task termination unless otherwise directed by agency management. The underlying data used for the model will be organized before the public comment phase of the project so that it can be easily shared upon request.

4 MODELING APPROACH

The following sections describe the modeling approach and model parameterizations, calibration and validation approaches, and the model's performance measures and evaluation criteria.

4.1 Modeling Approach Overview

The modeling approach for the LWSC system can be described in several steps.

1. **Develop the model grid.** The model grid scale is primarily driven by the area and processes of interest for the study. Boundary conditions should be a sufficient distance from the area of interest to reduce the impact of boundary condition uncertainty, especially in the case of open boundary conditions. To meet these requirements, the current LWSC model grid has been refined through the Montlake Cut, Portage Bay, Lake Union, Frement Cut, and Salmon Bay. The model grid also includes alignment with the Ballard Locks so that parameterizations can be developed for lockage activity through hydraulic structure equations.

2. **Model boundary conditions.** The model boundary conditions are ideally derived from known discharge or tidal stage locations. Such information is available from publicly available sources. The model boundary conditions must also be evaluated for mass balance closure in the case of flow and tidal boundaries. The mass balance for the LWSC model also includes approximations of evaporation or precipitation over the lake surface, which can be highly spatially variable across large lakes like Lake Washington.

3. **Model parameterizations.** Several factors within the EFDC+ model domain are required to complete the mass, momentum, and energy equations in a 3-dimensional system. The sensitivity of the model output to the value of these parameters varies widely, and many can be selected based on literature or approximate values used in previous studies.

4. **Model calibration and validation.** Observations collected within the model domain can sometimes calibrate and validate a model through quantitative and qualitative measures, including statistics and plots.

5. **Model performance measures.** Both statistical and graphical comparisons can be useful for evaluating the model's performance. The specific methodology or presentation of data will be described.

6. **Model evaluations.** Finally, the conditions for model evaluation will be described. This process includes recommendations based on the model's performance, and information for refining future data collection programs is also provided.

4.1.1 EFDC Model Parameterization

Table 4.1 lists the significant model parameters and estimation methods for EFDC. Parameters may then be added or dropped depending on the sensitivity analysis results. Several model coefficients and parameters were adjusted within reasonable ranges during calibration to achieve the best results.

Table 4.1: Model Parameters for hydrodynamics, salinity, and temperature in EFDC+

Parameter	**Module**	**Estimation Method**
Bottom roughness height (m)	Hydrodynamic	Calibration parameter
Smagorinsky coefficient (dimensionless)	Hydrodynamic, Salinity	Calibration parameter
Vertical eddy viscosity (m^2/s)	Hydrodynamic, Salinity	Calibration parameter
Vertical molecular diffusivity (m^2/s)	Hydrodynamic, Salinity	Calibration parameter
Surface Heat Exchange	Temperature	Calibration parameter
Light Attenuation	Temperature	Calibration parameter
Turbulence Closure	Hydrodynamic, Temperature, Salinity	Calibration parameter
Bottom Heat Exchange	Temperature	Calibration parameter

4.2 EFDC Calibration and Validation Approach

Model calibration and validation are necessary because of the inherent uncertainty of simulating environmental conditions using simplified mathematical representations of complex systems. Mechanistic models are based on physical, chemical, and biological processes that use kinetics derived from previous research or applications to quantify these processes mathematically. Model calibration is adjusting model parameters and kinetics to achieve an optimal match between the model's predicted output and the observed conditions. Model calibration involves a qualitative graphical comparison and basic statistical methods to compare model predictions and observations. To provide a credible basis for predicting and evaluating environmental scenarios and management options, the model's ability to represent real-world conditions should be optimized and evaluated through a model calibration process and, if appropriate, through validation (USEPA, 2002).

Following are the model state variables to be compared to observed data:

1. Water surface elevation (m)

2. Temperature (deg C)

3. Salinity (ppt)

DSI originally built two historical models to simulate water temperature between 2008 and 2019 (the Lake Washington Demonstration Model[6]), and a real-time model (the Lake Washington Real-Time Model[7]). However, these models only simulated temperature, and the grids extended westward to the Freemont Bridge.

DSI has since developed the model to include Shilshole Bay, and saltwater exchange through the locks has been included through direct parameterization of lock chamber closure and filling/emptying operations. The model has now been calibrated to the following state variables: water surface elevation, temperature, and salinity. The model parameters have been adjusted manually during model calibration.

This study uses a combined calibration and validation period from January 2018 to January 2022. This period is sufficiently long to account for uncertainty due to seasonal and inter-annual variations, typically accomplished by simulating multiple shorter periods (*i.e.*, discrete calibration and validation periods). In this manner, the study results can be presented more concisely. Therefore, the model will be validated to observed measurements collected per the data listed in Table 3.4.

4.3 Selection and Interpretation of Model Performance Statistics

The section will summarize the rationale for selecting model performance statistics for each parameter of interest in the current study. Guidance for interpretation will also be provided.

The selection and interpretation for this study was guided principally by an understanding of the:

- Mathematical construction of each statistic;
- Conceptual behavior of the system with regards to each parameter of interest; and
- Expected behavior and limitations of the statistic in the model.

On this basis, a reasonable criterion for model performance has been developed and applied in terms of station and aggregate statistics, where possible.

Numerous statistics exist in academic literature to evaluate model performance. However, it is often difficult to reproduce results or apply similar criteria without a precise definition for the

[6] `https://www.eemodelingsystem.com/modeling-resources/demonstration-models/dm-15-lake-washington-sigma-zed-model`

[7] `https://lakewashington.dsi.llc/`

statistics used (*i.e.*, many papers do not routinely provide statistical definitions or sometimes use different terminology for the same statistic). More broadly, there is no accepted overarching guidance for which statistics to use and how to interpret them, although several studies exist that seek to do so (see for example Arhonditsis and Brett, 2004, Moriasi et al., 2015, and Harmel, Baffaut, and Douglas-Mankin, 2018). For example, some statistics gain broad acceptance but may be ill-suited to a specific problem, provide confusing results given other information, provide insufficient information to distinguish between models, or could be skewed through filtering or averaging observational data or model predictions. The discussion in this section aims to provide a clear discussion regarding the nature of each statistic while considering prior work and experience in developing reasonable criteria for describing model performance qualitatively.

Therefore, this section aims to provide detailed definitions of each statistic used in this study, describe why the statistic was selected in terms of the conceptual behavior of the LWSC, and clearly describe the expected behavior, limitations, and criteria for interpretation.

4.3.1 Definition and Analysis of Performance Statistics

A broad array of model performance statistics were evaluated for application in this study. An exhaustive list of all available statistical parameters in EFDC+ Explorer is available in Appendix E. Only the selected statistics for each parameter are defined and analyzed in this section for brevity.

The mean of the observed value $\overline{O}$ is computed as:

$$\overline{O} = \frac{1}{N}\sum_{i=1}^{N} O_i$$

and the Mean Predicted value $\overline{P}$ is:

$$\overline{P} = \frac{1}{N}\sum_{i=1}^{N} P_i$$

The Mean Error (ME) is the difference between the average of the predicted and observed values:

$$ME = \overline{P} - \overline{O}$$

Where values of ME closer to zero indicate better model performance, note, however, that a large predicted variance, where large errors occur in the positive and negative direction relative to the observations, can effectively cancel out, producing a deceivingly small ME.

The Mean Absolute Error (MAE) provides a similar measure to the ME, with the exception that, by taking the absolute deviation between the observed and predicted value, large positive or negative errors contribute to the MAE in the same direction:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|P_i - O_i|$$

The MAE can, therefore, more accurately reflect differences between the observed and predicted values.

The Root Mean Square Error (RMSE) reflects the standard deviation of the differences between the observed and predicted values. The RMSE is computed as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2}$$

Combined with the MAE, which quantifies the absolute error, the RMSE provides a quantification of the standard deviation of the errors.

The Scaled Root Mean Square Error (SRMSE) is the RMSE normalized by the observed variance of the observations:

$$SRMSE = \frac{RMSE}{O_{max} - O_{min}} \times 100\%$$

The SRMSE is particularly useful for cases where the observed mean is close to zero, but a large range of variance is observed. In comparing stations where the range of a particular value, such as salinity or water surface elevation, can be large relative to the mean value and vary significantly from station to station, the SRMSE provides a valuable measure of model performance overall, keeping the errors in perspective relative to the overall range of the observations.

The Centered Root Mean Squared Error (CRMSE) relates three statistical measures: the correlation coefficient between the observed and predicted values (R), and the standard deviation of the observed σ_{obs} and predicted σ_{pred} values.

$$CRMSE = \sqrt{\sigma_{obs}^2 + \sigma_{pred}^2 - 2R\sigma_{obs}\sigma_{pred}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\left(P_i - \overline{P}\right) - \left(O_i - \overline{O}\right)\right]^2}$$

The Nash-Sutcliffe Index of Efficiency (NSE) varies from $-\infty$ to +1, with values close to 1 considered optimal. NSE values less than 0 indicate unsatisfactory model performance.

$$NSE = 1 - \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} \left(O_i - \overline{O}\right)^2}$$

In terms of the other statistics described thus far, the NSE can also be written as:

$$NSE = 1 - \frac{RMSE^2}{\sigma_{obs}^2}$$

Thus the NSE rewards models with a small standard deviation of errors relative to the standard deviation of the observations.

The RMSE is helpful to support the NSE, as the NSE is sensitive to the standard deviation between the model and data and the standard deviation of the observations, as discussed in detail in Appendix E. The NSE and KGE provide a statistical measure with a maximum of one but are based on fundamentally different formulations. The NSE is based on the squared error between the model and data at each observation point and the mean of the observed data. On the other hand, KGE decomposes the contribution of the mean, variance, and correlation to the model performance. Both are frequently cited and used in environmental and hydrologic modeling studies. In this study, for brevity, we provide the average of the NSE and KGE as the Model Skill Score in the below analysis.

4.3.1.1 Selected Statistics for Time Series and Vertical Profile Stations

Water Surface Elevation The selected statistics for water surface elevation (WSE) include the Mean Observed, Mean Predicted, Mean Error (ME), Mean Absolute error (MAE), Maximum Absolute Error (MaxAE), Root Mean Square Error (RMSE), and Model Skill Score (the average of the NSE and KGE). These statistics were selected for Water Surface Elevation to provide a detailed summary of the model performance. The water levels in Lake Washington are closely regulated by the US Army Corps of Engineers at the Ballard Locks and follow a predictable seasonal fluctuation.

Model predictions of the water surface elevation are an essential reflection of the model's ability to capture seasonal changes in the mass balance of the lake, as they reflect a balance between surface inflow, outflow, evaporation, and surface precipitation. Groundwater flux is also considered in the model and is constrained through mass balance closure analysis.

Generally, it can be anticipated that the model will produce predictions that are very close to the observed values and should produce a similar mean value. Therefore, we anticipate most of the selected statistics will produce close to optimal values for WSE. To provide a more critical perspective, we include the calculated maximum absolute error, which identifies the single largest error at any point during the simulation. Therefore, the MaxAE provides a clear measure of the maximum likely error of the model predictions.

Temperature The selected statistics for time series stations include the mean observed, mean predicted, ME, MAE, RMSE, SRMSE, and Model Skill Score.

As with WSE, several basic statistics can be easily computed to allow for quick framing of the overall model-data comparison for temperature. These include the mean observed, mean predicted, mean error, and mean absolute error.

The RMSE is a useful complement to these basic statistics and the Model Skill Score (defined as the average of the NSE and KGE). By squaring the error, errors in different directions no longer cancel out (*i.e.*, errors all contribute in the same direction, unlike the mean error, for example). This is similar to the mean absolute error, however, the RMSE, due to being the squared error, will penalize errors greater than 1 (regardless of the statistic). Therefore, systematic errors in the model can contribute to an RMSE somewhat higher than the mean absolute error or mean error.

The logic regarding the skill score defined for WSE is similar to that used for temperature. Simply put, both statistics reflect different statistical concepts but have been found to serve as reliable indicators for various environmental parameters of interest, including temperature.

The selected statistics for vertical profile station comparisons include the mean observed, mean predicted, ME, MAE, CRMSE, and Model Skill Score.

As with the time series stations, the basic statistics for vertical profiles include mean observed, mean predicted, ME, MAE, and the Model Skill Score. For vertical profiles, the CRMSE was also selected.

While the concept of the CRMSE concept is similar in some regards to the KGE, the advantage of the CRMSE for vertical profiles is that it provides a relative measure in terms of the input units (*i.e.*, degrees C). Since the CRMSE accounts explicitly for both the mean observed and predicted values, as well as the deviation from those values, the spread of the model and data, and the linearity of the overall data, it is a good fit for vertical profiles where similarities in the shape, as well as the mean of the model and data, can be weighed more heavily.

The below criteria generally describe the interpretation of the model with regard to these statistics. Note that the model predictions or a station do not have to meet all the criteria to be described qualitatively with the below terms.

Acceptable — MAE/CRMSE less than 2.5 C, RMSE less than 3 C, Scaled RMSE less than 50%, Skill Score greater than 0.5

Good — MAE/CRMSE less than 2 C, RMSE less than 2.5 C, scaled RMSE less than 25%, Skill Score greater than 0.75

Excellent — MAE/CRMSE less than 1 C, RMSE less than 1.5 C, scaled RMSE less than 10%, Skill Score greater than 0.9

Salinity statistics for time series stations include ME, MAE, RMSE, and SRMSE. These statistics were selected because salinity tends to vary strongly within the LWSC. Strong variations can be observed horizontally, vertically, and seasonally. At LLLW, salinity can vary between 0 and 23 ppt, at BBLW between 0 and 15, at FBLW between 0 and 10, and GWLW between 0 and 15 ppt. At UBLW, salinity is typically close to zero and was not observed to exceed 1 ppt during the period of study. Large changes in salinity can occur suddenly due to failures in the saltwater drain, and these rapid changes cannot be directly inferred from any of the presently available data. Therefore, the challenges for modeling salinity and selecting appropriate statistics to base the model calibration process are challenging.

In general, the large range and spatial variation of salinity in LWSC make the selection of statistics difficult. Although concentrations can be quite small for significant periods of time (and the models tend to capture similarly small concentrations), observations of salinity can be relatively insensitive to small changes in the environment, leading to a ”stair-step” pattern in the observation data which is an artifact of the instrument. Therefore, variance-based measures of model performance will generally be very poor, as can be seen from the NSE for example, where a denominator approaching zero could be possible if individual observations are all close to the mean observed concentration. Therefore, we have opted against the use of variance-based measures such as the NSE and KGE. Instead, model performance in this study will be based on the instantaneous error relative to the range of the observations at each station. These statistics have been selected because they provide a meaningful reflection of the performance of the model at each station, controlling for large differences in the observed range and the instantaneous magnitude of any model error.

As before, we will also note that the RMSE generally penalizes errors greater than 1 due to errors being squared, so large errors will impact these RMSE and scaled RMSE more significantly. In general, we define the following qualitative terms to describe the model performance for salinity based on the following criteria for each station.

Acceptable — Less than 100% SRMSE

Good — Less than 50% SRMSE

Excellent — Less than 20% SRMSE

4.3.1.2 Aggregate Statistics for Temperature and Salinity

For aggregate time series statistics regarding the model performance for Temperature and Salinity, the primary measure will be the Model Skill Score. As with the criteria established for time series temperature stations, the following qualitative descriptions have been defined to support the discussion of the model performance.

Acceptable — greater than 0.5

Good — greater than 0.75

Excellent — greater than 0.9

5 MODEL DEVELOPMENT

5.1 Model Grid

A computational curvilinear grid was developed for the model. The unit system is metric, the projection or horizontal datum is NAD83 UTM 10N, and the vertical datum is NAVD88. The 3-Dimensional EFDC+ model consists of 2683 horizontal curvilinear grid cells with 197 rows and 79 columns. For vertical layering, the model uses the Sigma-zed (SGZ) option with a specified bottom layer. The SGZ approach enables flexibility in the number of vertical layers across the model domain, resulting in improved computational efficiency and reduced pressure gradient errors (Craig et al., 2014) compared to other approaches. The specified bottom layer approach determines layer thicknesses based on maximum depth. Currently, the model employs between 3 and 70 vertical layers.

5.2 Boundary Conditions

5.2.1 Open Boundary Condition

The boundary conditions data for the models were provided from the measurement gauge stations available within and near the computational grid. Starting with the open boundary, this model uses one water level north open boundary where the LWSC is connected to Shilshole Bay. Tidal data were downloaded from NOAA Tides and Currents, salinity is set to 28.5 ppt at both the surface and bottom, and the water temperature is based on the monthly water temperature at Seattle.

5.2.2 Flow Boundary Conditions

Freshwater flow boundary conditions are vital inputs for hydrodynamic models, especially when simulating water bodies influenced by rivers or other freshwater sources. These boundary conditions represent the inflow of freshwater at the model's boundaries. The LWSC model uses 8 flow boundary conditions, as shown in Table 5.1. Except for the Cedar and Sammamish River flow boundaries, all flow boundaries are assigned to only one cell. Each of these flow boundaries is associated with its own unique temperature time series.

Table 5.1: Baseline model flow boundary conditions.

Flow Boundary Name	Average Discharge (m^3/s)
KingCo34a	0.1413
KingCo35C	0.3493
KingCo27a	0.2957
KingCo58a	0.2525
KingCo37A	0.6394
KingCo-COB-06C	0.4166
Cedar River	21.0399
Sammamish River-51T	10.1459

5.2.3 Withdrawal/Return and Hydraulic Structure Boundary Conditions

To simulate the spillway, the fish ladder, and the small and large chambers of the Ballard locks, withdrawal/return boundaries are used. Figure 5.1 demonstrates these boundary conditions. The hydraulic structures used include three gates for the large chamber and two for the small chamber, which are also the location of inflow and outflows of the withdrawal/return boundaries.

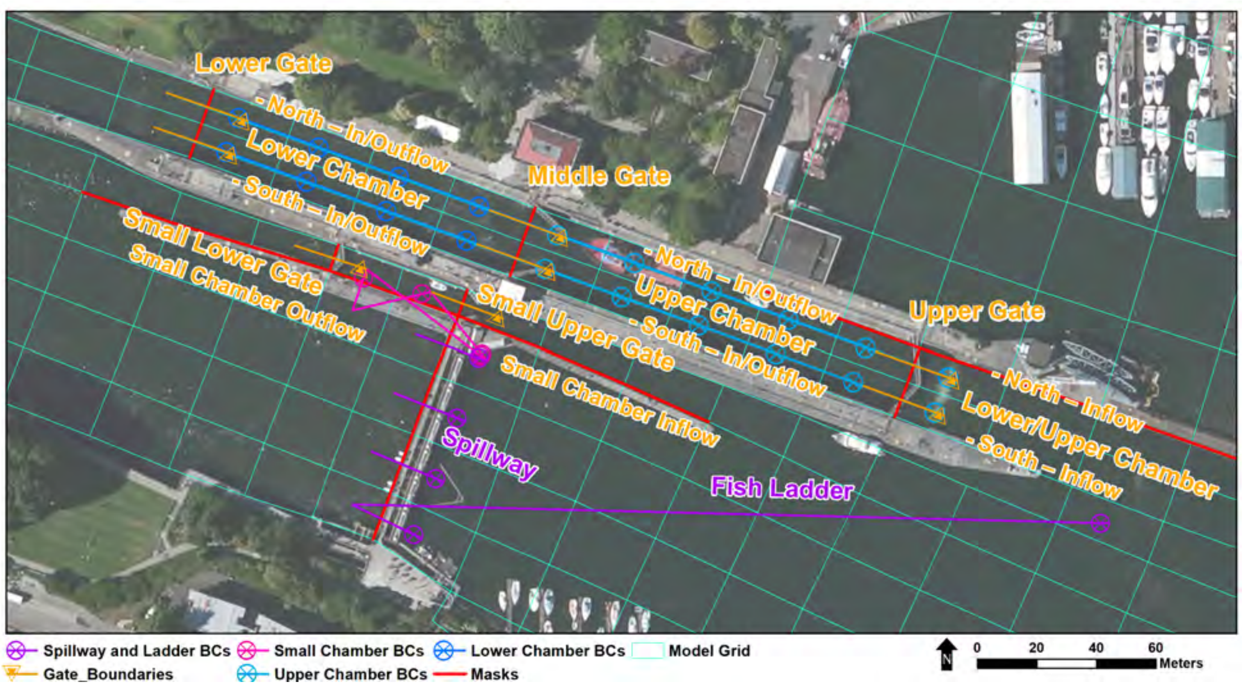

Figure 5.1: Withdrawal/return boundaries and hydraulic structures.

5.2.4 Atmospheric and Wind Boundary Conditions

Atmospheric and wind boundary conditions are crucial in accurately representing the interactions between water bodies and the atmosphere. These boundary conditions encompass the atmospheric variables influencing hydrodynamics, such as air temperature, wind speed, wind direction, and atmospheric pressure, as can be seen in Figure 5.2. To define the atmospheric boundary conditions, this study used historical meteorological data from 4 nearby weather stations.

Wind boundary conditions affect water surface elevations, circulation patterns, and mixing processes. It is essential to consider spatial variations in wind conditions, especially across the large surface areas of Lake Washington and Lake Union. To define the wind boundary conditions, the model uses wind data from 5 stations shown in Figure 5.2; these wind stations are blended by location using inverse distance weighting.

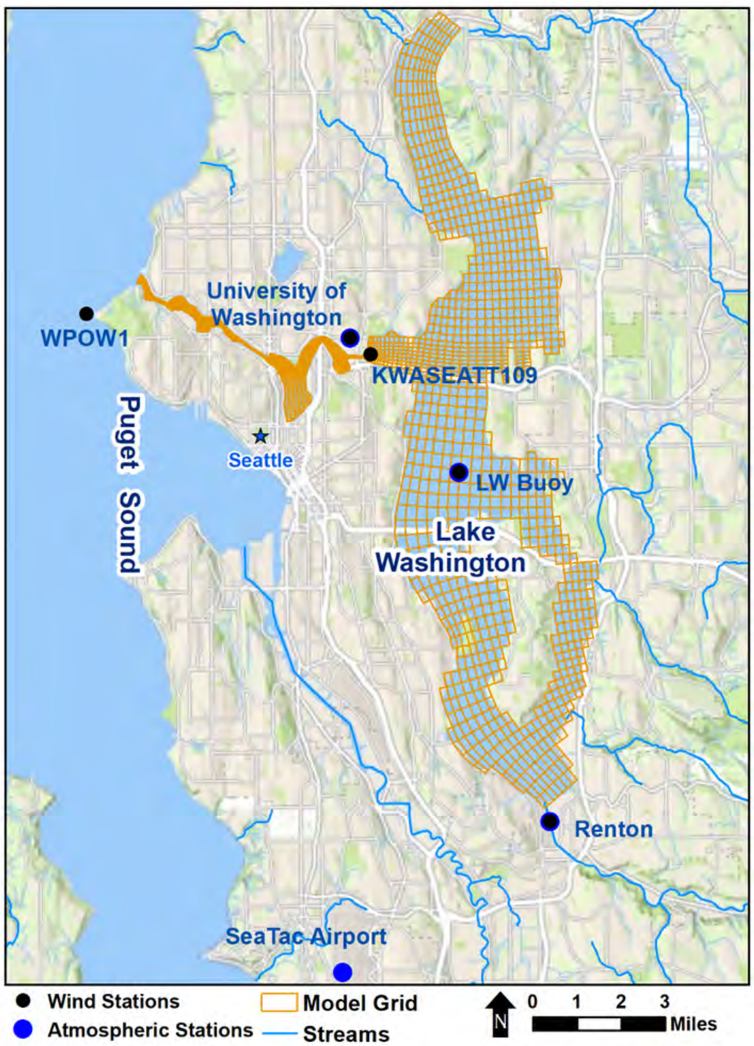

Figure 5.2: Surface boundary condition stations.

5.3 Initial Conditions

5.3.1 Bathymetry

Bathymetry refers to measuring and mapping water depths in bodies of water. Accurate bathymetric data is essential for navigation, water resource management, ecological studies, and other purposes. Bathymetric surveys have been conducted to create detailed maps of the lake and canal, providing valuable information about the underwater topography, depths, and contours. The bathymetry of the model domain, including Lake Washington, Lake Union, and the LWSC, is shown in Figure 5.3. The bathymetry data is derived from several sources. Initial bathymetry was specified as a cell-level average obtained from the NOAA dataset. The navigation charts from NOAA assessed the shoreline and areas where buildings or shoreline bulkhead elevations may have impacted bathymetric data collection. Sounding data outside the navigation channel from NOAA was used to check the topo-bathymetric data. Finally, the navigation channel and Lake Union bottom elevations were derived from the 2000 survey. This was used to overwrite the elevation from all previous sources. Table 5.2 provides a list of sources used to derive bathymetry data.

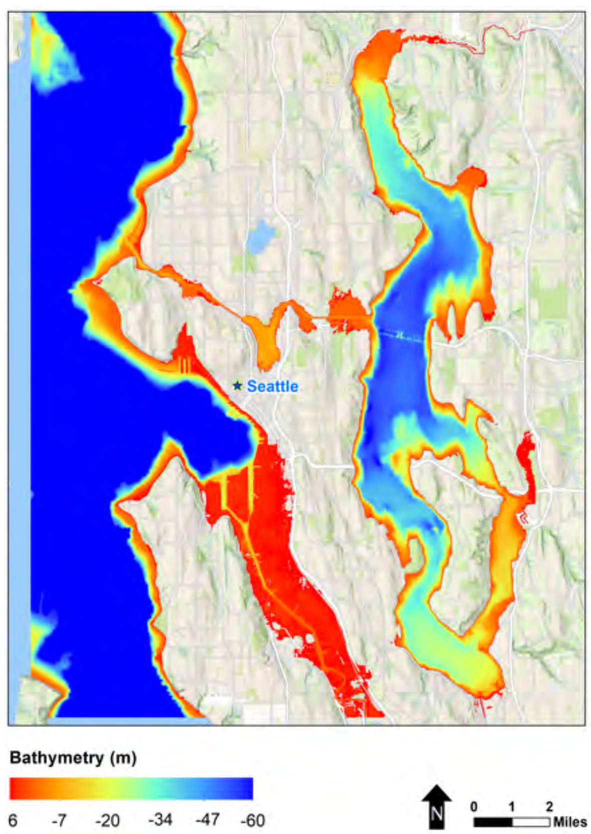

Figure 5.3: Bathymetry of the study area.

Table 5.2: Bathymetry data sources.

Data Name	Data Sources
Initial Bathymetry	https://www.fisheries.noaa.gov/inport/item/59971
Navigation Charts	https://www.charts.noaa.gov/OnLineViewer/18447.shtml
Sounding Data	https://encdirect.noaa.gov
2000 Hydrographic Survey	http://bit.ly/44J3rzY

5.3.2 Initial Conditions for Temperature

Defining the initial temperature for a hydrodynamic model simulating the LWSC requires careful consideration of the lake's thermal characteristics and available data. Several factors influence the initial temperature, including seasonal variations, solar radiation, air temperature, and water inflows. One approach is to use historical temperature data for the lake, considering long-term trends and seasonal patterns. Historical measurements from monitoring stations or research studies can provide valuable insights into temperature variations throughout the year. Analyzing this data can identify the average temperature range and notable trends or fluctuations. Lake Washington's initial conditions for temperature are based on observed data and vertical profiles from the LW Buoy station (refer to Figure 5.2). The temperature vertical profile from the LW Buoy station on January 2nd, 2023 is used as the initial condition for temperature.

5.3.3 Initial Conditions for Salinity

Lake Washington's initial salinity of zero ppt was used. Salinity's initial condition in the LWSC was set to 0.04 ppt and 28.5 ppt in Shilshole Bay. Then simple interpolation was used horizontally for stations at other depths based on observed conditions.

5.3.4 Initial Condition for Water Level

It was crucial to establish the appropriate initial water levels for the sea, lake, and lock chambers to ensure stability in the simulation. For the large lock, the lower chamber was established as commencing at sea level, while the upper chamber begins at lake level. In the case of the small lock chamber, its initial condition was established as aligning with the sea level. The sea level was set at -0.243 meters, while the lake level was configured to 6.099 meters. Accurately defining these initial water levels makes it possible for the model to initiate a stable and reliable simulation.

6 MODEL CALIBRATION AND VALIDATION

6.1 Simulation Period

The LWSC model's combined calibration and validation period is from January 2018 to January 2021. The calibration and validation process included adjusting model parameters mentioned in Section 6.4 to get the best fit between the observed and simulated outputs. Graphical comparisons between model outputs and observations were made in addition to evaluating statistics. The simulation results were compared to observation data for three state variables at multiple stations: water surface elevation, temperature, and salinity. The calibration process was performed manually rather than using an automated method.

6.1.1 Calibration Parameters

Several model parameters selected based on a sensitivity analysis were adjusted in the process of calibration. The initial parameter values can be set based on existing knowledge, literature, or preliminary simulations. The calibration process then involves adjusting these parameters iteratively to optimize the model's performance and match the observed water surface elevation, salinity, and temperature patterns.

Table 6.1 lists the parameters used for model calibration in the temperature module and their calibrated values. The following EFDC+ model options were used in the temperature module to represent the processes more accurately:

1. The full heat balance surface heat exchange sub-model was used (Legacy).
2. The surface heat transfer coefficients were set to vary with the wind speed.
3. Solar radiation was distributed over the water column using extinction coefficients.

Table 6.1: Calibration temperature parameters in EFDC+.

Parameter	Calibrated Value
Surface heat transfer coefficients Evaporation heat transfer (dimensionless scaled by 1000)	1.75
Surface heat transfer coefficients Convective heat transfer (dimensionless scaled by 1000)	1.75
Light extinction Fast coefficient(1/m)	0.6
Light extinction Slow coefficient(1/m)	0.3
Light extinction Fraction attenuated fast (1/m)	0.8
Bottom heat exchange Heat transfer coefficient (m/s)	1.1965e-10
Bottom heat exchange Convective heat transfer coefficient (dimensionless)	0

Tables 6.2 and 6.3 list the parameters used for model calibration for the hydrodynamics and horizontal and vertical turbulence and their calibrated values. The following EFDC+ model options were used in the hydrodynamics turbulence sections to represent the processes more accurately:

1. Smagorinsky subgrid turbulence formulation was used with a coefficient value of 0.11.
2. Background horizontal momentum diffusivity was set as spatially varying as a function of cell size, with an average value of 2.
3. The closure model selected was a second order k-ε approach, using a Algebraic Reynolds Stress Model (Canuto et al., 2001).
4. Other general settings for the GOTM module have been provided in Table 6.3.
5. Maximum eddy viscosity and diffusivity were used.

Table 6.2: Calibration hydrodynamics, turbulence parameters in EFDC+.

Parameter	Calibrated Value
Vertical eddy viscosity Background eddy viscosity (AVO, m^2/s)	1e-05
Vertical eddy viscosity Max. kinematic eddy viscosity (AVMX, m^2/s)	0.1
Vertical eddy diffusivity Background eddy diffusivity (ABO, m^2/s)	5e-06
Vertical eddy diffusivity Max. eddy diffusivity (ABMX, m^2/s)	0.15

Table 6.3: GOTM turbulence options.

Parameter	**Selected Option**
Turbulence Closure	Second-Order
TKE Equation	Differential Equation for Turbulent Kinetic Energy (k-ε style)
Length Scale Method	Dynamic Dissipation Rate equation
Second-Order Method	Algebraic Non-Equilibrium Closure Model (Canuto et al., 2001)

6.1.2 Calibration Stations

The calibration stations were selected locations within the water body where continuous temperature and salinity measurements were collected. The calibration process involves comparing the model's outputs with the observed data from these stations to adjust the model's parameters. The selection of calibration stations is based on several factors, including the spatial distribution of the stations to capture the variability of temperature and salinity across the water body. Differences between the model and the real system can be identified by comparing the model's outputs with the observed data from these stations. Figure 6.1 illustrates the location of stations that provided observed data used for calibration and validation of the LWSC model. Table 6.4 shows the key stations used for calibration and validation; the data sources are USACE and King County.

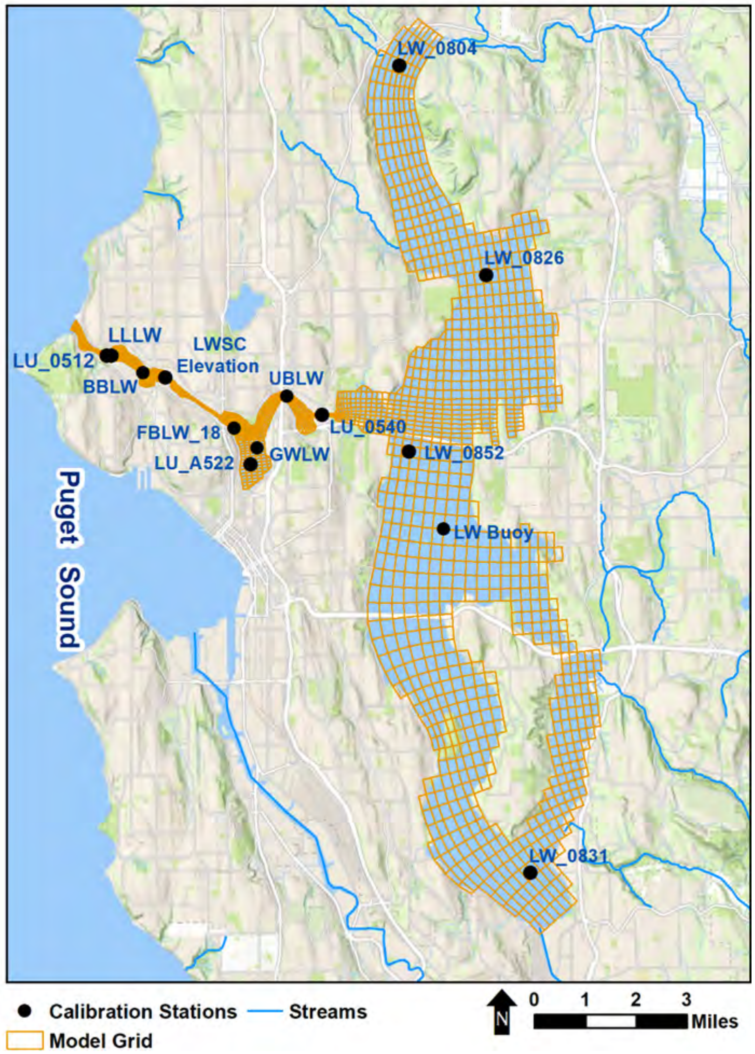

Figure 6.1: Observed data stations.

Table 6.4: Key stations for calibration/validation.

Station Name	Measured Parameters	Latitude	Longitude
LU_0512	Water Temperature	47.66469	-122.396203
LU_0540	Water Temperature	47.647299	-122.305248
LU_A522	Water Temperature	47.632605	-122.338043
LW_0804	Water Temperature	47.746765	-122.271239
LW_0826	Water Temperature	47.686760	-122.235333
LW_0831	Water Temperature	47.515852	-122.219080
LW_0852	Water Temperature	47.636495	-122.268664
LW Bouy	Water Temperature	47.630078	-122.253837
BBLW	Water Temperature, Salinity	47.664902	-122.394641
FBLW	Water Temperature, Salinity	47.645548	-122.345979
GWLW	Water Temperature, Salinity	47.652860	-122.330429
UBLW	Water Temperature, Salinity	47.625860	-122.320115
LLLW	Water Temperature, Salinity	47.664902	-122.394641
WSE	Water Surface Elevation	47.646718	-122.346402

6.1.3 Calibration Graphics

Calibration graphics are essential when comparing measured and simulated salinity and temperature in a hydrodynamic model. These graphics visually represent the observed data and the model outputs, allowing for a comprehensive assessment of the model's accuracy and performance. They aid in fine-tuning the model parameters to minimize discrepancies and improve the model's reliability. Calibration graphics are a powerful tool for validating and refining hydrodynamic models, ultimately enhancing our understanding of complex water systems.

6.1.3.1 Water Surface Elevation

The LWSC hydrodynamic model simulates the water surface elevation (WSE) accurately. The calibration plot comparing observed and simulated water surface elevations at LWSC Elevation station is shown in Figure 6.2 confirms the models' great performance. As can be seen, the blue line which shows the model predictions of water surface elevation has a great alliance with the red line which shows the observed data.

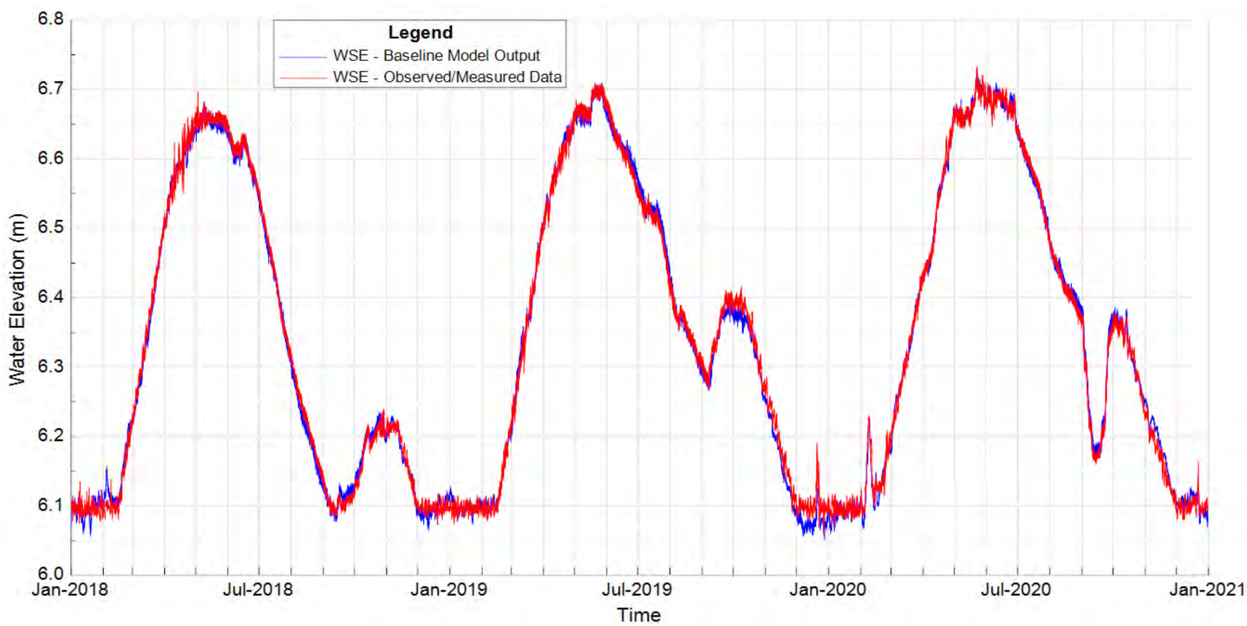

Figure 6.2: Water surface elevation (WSE): baseline model output vs. observed/measured data at the LWSC Elevation station.

Table 6.5 summarizes the model performance statistics selected for water surface elevation in Section 4.3.1.1. The statistics shown provide confirmation of the excellent model performance for water surface elevation and, therefore, mass balance as a proxy.

Table 6.5: Summary of the model performance statistics for water surface elevation (WSE; m).

Parameter	Units	$\overline{O}$	$\overline{P}$	ME	MAE	MaxAE	RMSE	Skill
WSE	m	6.341	6.340	-0.001	0.01	0.075	0.013	0.997

6.1.3.2 Temperature and Salinity

The present section summarizes the Baseline model calibration for temperature and salinity by primarily focusing on statistical evaluations following the discussion in Section 4.3. Detailed graphical overviews of the Baseline Model calibration for selected stations are provided in Appendix A. These plots visually illustrate and highlight the similarities and differences between the actual recorded values for these parameters and the data generated through the simulation process. In addition to the statistical summary tables in this section, a complete list of all time series station statistics for the Baseline model has been provided in Appendix B.

Tables 6.6, 6.7 and 6.8 show the model performance by comparing observed versus simulated temperature and salinity using several statistics. Table 6.6 shows that for temperature, only the deepest Gas Works Park, and Freemont Bridge stations (GWLW_36ft, and FBLW_40ft) fall outside the acceptable range. As for the temperature vertical profile evaluations, all the LW stations have an RMSE of less than 2 °C, and have model skill scores greater than 0.85, which meet the criteria established for excellent model performance.

According to Table 6.8 for salinity, only the Ballard Bridge (BBLW_21ft) was found to provide acceptable model performance (100% $<$ SRMSE $<$ 50%). In contrast, all other stations provided good or excellent model performance compared to the data. Although the model performance demonstrated here is generally very good, further model performance improvements could be anticipated through an improved understanding of the saltwater drain flow rate or potentially increased grid resolution near the upstream gate of the Large Lock.

Table 6.6: Calibrated model statistics comparing observed vs. simulated temperature station (degrees C, unless otherwise indicated) by the station from the LWSC stations.

Station ID	**Depth (m)**	$\overline{O}$	$\overline{P}$	**ME**	**MAE**	**RMSE**	**SRMSE**	**SS**
LU_0540_1m	1.000	15.450	15.650	0.200	0.539	0.648	3.810%	0.967
LU_0540_5m	5.000	15.261	15.158	-0.102	0.505	0.631	3.802%	0.970
UBLW_6ft	1.830	17.215	17.388	0.173	0.401	0.537	2.964%	0.977
UBLW_21ft	6.400	16.689	16.204	-0.485	0.699	0.915	5.145%	0.950
UBLW_35ft	10.670	15.750	14.929	-0.822	0.969	1.254	7.259%	0.914
GWLW_3ft	0.910	17.486	17.686	0.200	0.473	0.602	3.322%	0.970
GWLW_13ft	3.960	17.268	17.572	0.304	0.535	0.682	3.909%	0.965
GWLW_25ft	7.620	15.888	16.061	0.173	0.528	0.670	3.927%	0.976
GWLW_36ft	10.970	12.976	14.652	1.675	2.221	2.915	22.814%	0.045
LU_A522_1m	1.000	14.760	15.099	0.339	0.532	0.707	4.420%	0.962
LU_A522_5m	5.000	15.207	15.457	0.250	0.515	0.676	4.170%	0.972
LU_A522_10m	10.000	13.810	13.668	-0.142	0.793	1.107	8.262%	0.928
FBLW_18ft	5.490	16.818	16.943	0.126	0.532	0.673	3.935%	0.975
FBLW_31ft	9.450	15.753	15.523	-0.230	0.689	0.872	5.567%	0.934
FBLW_40ft	12.190	13.577	15.182	1.605	1.996	2.934	20.313%	0.246
BBLW_11ft	3.350	16.588	17.117	0.529	0.682	0.873	5.257%	0.943
BBLW_21ft	6.400	16.375	16.341	-0.034	0.511	0.664	4.148%	0.961
BBLW_32ft	9.750	16.375	15.773	-0.602	0.869	1.035	6.469%	0.954
LU_0512_1m	1.000	14.626	14.792	0.167	0.491	0.656	3.834%	0.956
LU_0512_5m	5.000	14.923	15.143	0.22	0.472	0.629	3.768%	0.952
LLLW_S1_D18	5.486	16.780	17.286	0.506	0.746	0.952	5.733%	0.928
LLLW_S1_D28	8.534	16.692	16.924	0.232	0.603	0.813	4.928%	0.932
LLLW_S1_D36	10.973	16.334	16.650	0.316	0.747	1.069	6.636%	0.920
LLLW_S1_D43	13.106	15.643	15.159	-0.484	0.840	1.096	6.973%	0.924

Table 6.7: Summary of model performance station-by-station vertical profile evaluation for temperature (degrees C, unless otherwise indicated).

Station ID	# Profiles	$\overline{O}$	$\overline{P}$	ME	MAE	CRMSE	SS
LU_0512	194	14.730	14.900	0.180	0.470	0.610	0.960
LU_0540	209	14.690	14.320	-0.380	0.850	1.230	0.940
LU_A522	868	13.830	14.200	0.370	0.910	1.450	0.920
LW_0804	187	14.380	13.840	-0.540	1.240	1.760	0.900
LW_0826	1,167	11.020	10.280	-0.740	0.980	1.190	0.910
LW_0831	899	11.410	11.580	0.170	1.310	1.920	0.860
LW_0852	1,860	11.110	10.550	-0.560	0.870	1.070	0.930
LW Buoy	215,669	9.900	9.180	-0.730	0.860	0.750	0.920

The statistics calculated for salinity include the mean observed, mean predicted, mean error (ME), mean absolute error (MAE), root mean squared error (RMSE), and scaled root mean square error (SRMSE). scaled RMSE is an extension of the traditional Root Mean Square Error that considers the range of the observed data. The primary motivation behind using scaled RMSE is to provide a normalized measure of prediction accuracy that is not affected by the scale of the data. Since the range of salinity in the study area is quite large, this statistic can show the results well.

Table 6.8: Calibrated model statistics comparing observed vs. simulated salinity (ppt, unless otherwise noted) station by station.

Station ID	Depth (m)	$\overline{O}$	$\overline{P}$	ME	MAE	RMSE	SRMSE
UBLW_6ft	1.830	0.040	0.001	-0.040	0.040	0.040	44.496%
UBLW_21ft	6.400	0.040	0.002	-0.038	0.040	0.040	44.841%
UBLW_35ft	10.670	0.050	0.010	-0.040	0.054	0.065	18.667%
GWLW_3ft	0.910	0.052	0.027	-0.025	0.046	0.054	26.976%
GWLW_13ft	3.960	0.053	0.029	-0.024	0.049	0.057	28.714%
GWLW_25ft	7.620	0.059	0.036	-0.023	0.057	0.072	20.056%
GWLW_36ft	10.970	0.731	0.095	-0.636	0.699	1.138	29.935%
FBLW_18ft	5.490	0.052	0.040	-0.012	0.043	0.055	29.119%
FBLW_31ft	9.450	0.085	0.170	0.085	0.131	0.197	23.17%
FBLW_40ft	12.190	0.328	0.399	0.071	0.364	0.574	12.693%
BBLW_11ft	3.350	0.087	0.074	-0.013	0.048	0.059	23.434%
BBLW_21ft	6.400	0.122	0.485	0.362	0.385	0.573	98.817%
BBLW_32ft	9.750	0.864	1.628	0.764	0.908	1.232	14.261%
LLLW_S1_D18	5.486	0.134	0.210	0.076	0.111	0.155	12.848%
LLLW_S1_D28	8.534	0.421	1.185	0.764	0.819	1.062	12.513%
LLLW_S1_D43	13.106	6.067	6.523	0.447	2.520	3.208	14.283%

6.2 Calibration and Validation Summary

Hydrodynamic model calibration is crucial in ensuring the accuracy and reliability of the model's predictions. It involves adjusting the model's parameters and settings to improve performance and align its output with observed data. A summary of model performance in simulating temperature, salinity, and water surface elevation as an aggregate of all time series stations is shown in Table 6.9.

Table 6.9: Summary of calibration statistics for temperature, salinity, and water surface elevation.

Parameter	**Skill Score**
Water Surface Elevation	0.997
Temperature	0.925
Salinity	0.765

In the 3 years from January 2018 to January 2021, the model predicted the temperature at most stations with good accuracy and precision (high aggregated SS and low aggregated MAE and RMSE). The most notable deviations were at the deepest Fremont Bridge, and Gas Works Park stations (FBLW_40ft, and GWLW_36ft).

As for salinity, mean observations indicated a low salinity environment at most shallow stations. Most salinity stations in the LWSC showed very low concentrations, only a few times higher than the minimum precision of the instruments. This can cause variance-based error statistics to suggest poor performance; hence, more emphasis is placed on Mean Absolute Error and SRMSE. The aggregate SS was also provided. The SRMSE is less than 50% at all stations except for BBLW_21ft station. As described in more detail below, this is likely a result of the model predicting a halocline that is too diffusive relative to the data, which in light of the dynamic and complex pycnocline across Lake Washington and LWSC, presents a significant challenge for the model calibration.

Although the SRMSE values at University Bridge were somewhat higher, closer inspection of the time series demonstrates that the instrument is reading close to the minimum level of precision, both in terms of distinguishing from values above 0 ppt and in terms of changes over time (*i.e.*, a notable stair-step pattern can be seen in the data). Based on an inspection of Figure 6.3, which is typical of the University Bridge data series for salinity, we believe that although model performance statistics might suggest otherwise, these stations are always generally close to the minimum value of the instrument and, therefore, can be considered effectively close to zero, and further, that the observed standard deviation is likely to be skewed towards near zero values due to a lack of instrument precision at low concentrations, and is therefore an unreliable basis for comparing model performance to observations.

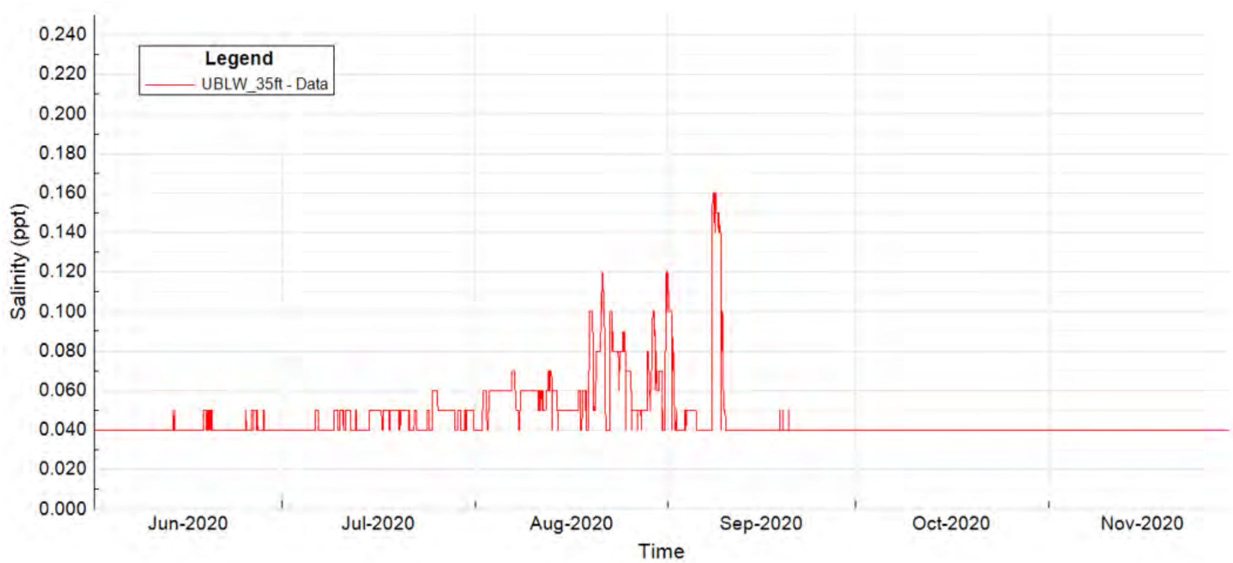

Figure 6.3: Example of a time series of salinity collected at the University Bridge station.

Stations with higher average salinity concentrations (*i.e.*, Large Lock, and Ballard Bridge) showed promising results. Model calibration involving double stratification, as is the case in the LWSC, often involves a trade-off between tuning the model in a way that helps maintain sharp density stratification (typically the case for large salinity gradients) or allows for a more diffusive gradient (typical of a variably mixed freshwater system). Often, it is possible to improve the performance of one parameter (such as temperature), but any improvements for one parameter often come at the cost of model performance for other parameters (*i.e.*, salinity). As we see in the case of salinity, the model under-predicted most often upstream of Fremont Bridge (*i.e.*, Gas Works Park, and University Bridge) and somewhat over-predicted at most stations downstream of Fremont Bridge (*i.e.*, Fremont Bridge, Ballard Bridge, and Large Lock stations). Notably, the model predicts somewhat more diffusive vertical gradients of salinity, which is a trade-off to enhance mixed layer deepening of the surface water layer during the critical summer season to improve model performance for temperature. The theoretical rationale for this trade-off comes from linking momentum, heat, and constituent diffusion rates in the turbulence closure model using the Turbulent Prandtl and Schmidt Numbers. Although a detailed discussion of this matter is beyond the scope of the current discussion, it warrants careful consideration in future studies. This finding indicates it may be beneficial to compare the model predictions to a more intensively collected data set, such as the lock operation evaluation dataset from the USACE.

7 SCENARIO DEVELOPMENT

7.1 Scenario Concept

The scenario applications in this study aimed to evaluate the potential impacts of cold water supplementation on the LWSC, and to what degree such a solution could enhance water quality and habitat suitability, thereby benefiting both young and mature salmon. Three scenarios were configured in this project. The scenario objective was to simulate a system intended to supplement cold water in the LWSC using 6-inch diffuser platforms deployed along the bottom of the channel.

The concept involves the strategic pumping of cold water into the bottom of the Montlake Cut, enabling it to flow downstream into the ship canal since there is a westward movement from Lake Washington to Puget Sound. This process serves two purposes: firstly, it effectively cools down the deeper waters, and secondly, it reduces barriers to fish passage.

7.2 Modeling Approach for Scenarios

A cold water barrier in the plans was represented in the model by simply increasing the bottom elevation to create a small sill in the bathymetry which was expected to limit the eastward flow of cold water. After testing, it was generally ineffective in changing the flow direction in scenario evaluation. Therefore, it was found that this approach may impact the retention of cold water, but only during periods where the outflow from the Ballard Locks was less than the diffuser discharge. This is because the flow through the Montlake Cut can be directly related to the outflow at the Ballard Locks.

The EFDC+ Jet/Plume module was used to capture the impact of diffusers. The Jet/Plume module uses an approach similar to CORMIX, whereby the near-field effects of high energy diffusers are accounted for and included not only in the cell where the boundary is located but also in the nearby cells. However, the additional detail gleaned using the Jet/Plume type boundary condition diminishes when excessively coarse grid resolutions are used. In the LWSC model, grid resolutions near the cold water supplementation locations were limited to less than 75 meters of horizontal resolution in the Montlake and Fremont Cuts. Given the 5-foot spacing between each diffuser, approximately 45 diffusers were present in each cell.

On the other hand, the vertical layers (the more substantial dimension for understanding the impacts of density stratification) in the LWSC were always set as less than one meter thick. This resolution, particularly in the vertical dimension, was sufficiently high to capture the impact of the diffusers on the vertical structure in terms of changes to overall temperature and density (*i.e.*, the diffuser water is less dense than any salt water around it close to the bottom). It was also sufficiently high to capture the impact of momentum changes (*i.e.*, the diffuser water already has vertical momentum and entrains some denser water upwards).

7.3 Scenario 1B Configuration

To implement Scenario 1B, the Jet/Plume boundary condition using a withdrawal return flow approach was employed. The determination of withdrawal and return cells and the allocation of ports within each cell was computed based on the plans provided by Jacobs shown in Figures 7.1 and 7.2. The current implementation of Scenario 1B also includes a subsurface cold water barrier in the defined location by Jacobs. Figure 7.3 shows the spatial arrangement of withdrawal and return cells. To adhere to the prescribed scenario configuration, two sets of diffusers were positioned along the 2,500 ft long and 4,700 ft long lines, allowing for the introduction of cold water into the lower section of the Montlake Cut.

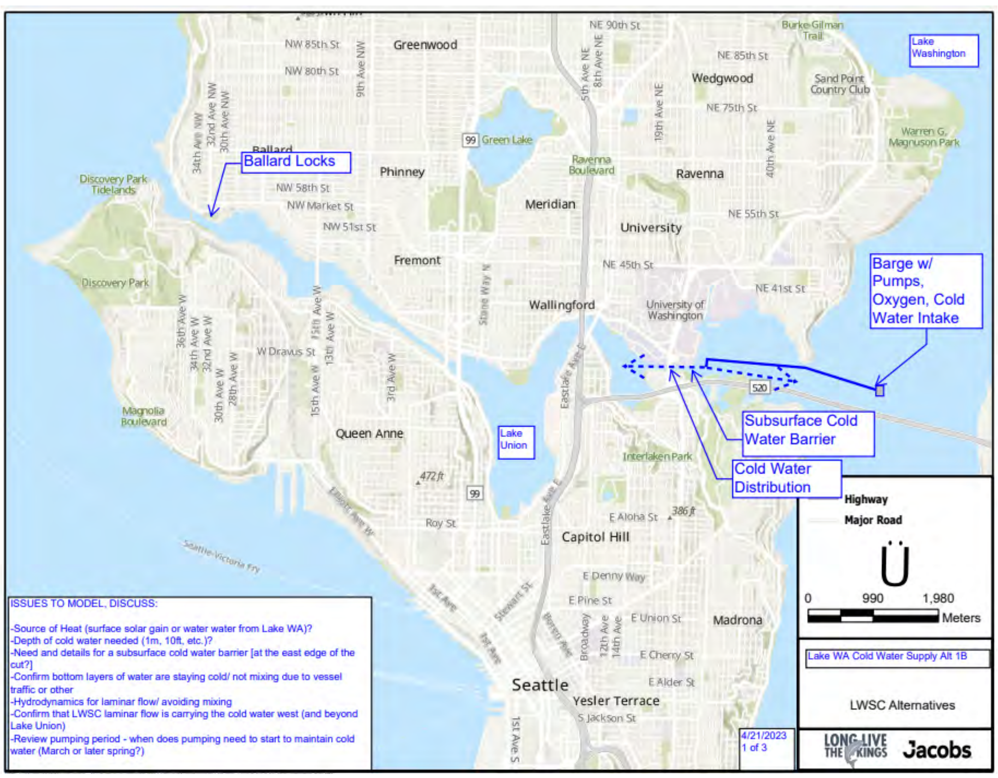

Figure 7.1: Scenario 1B from Jacobs.

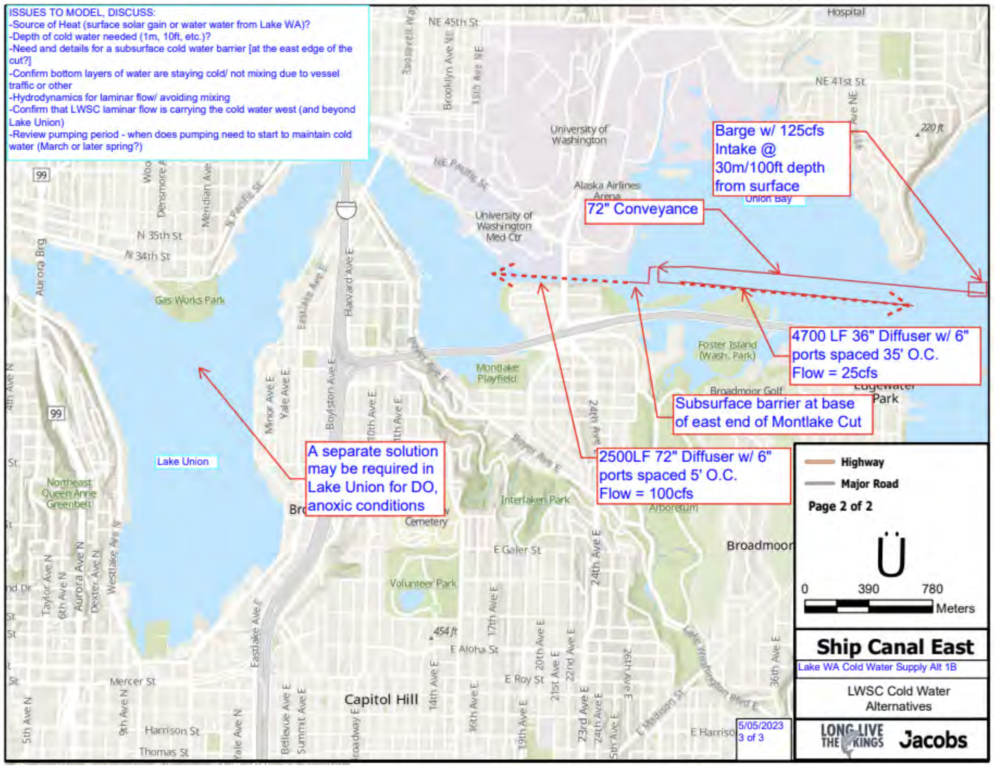

Figure 7.2: Scenario 1B from Jacobs.

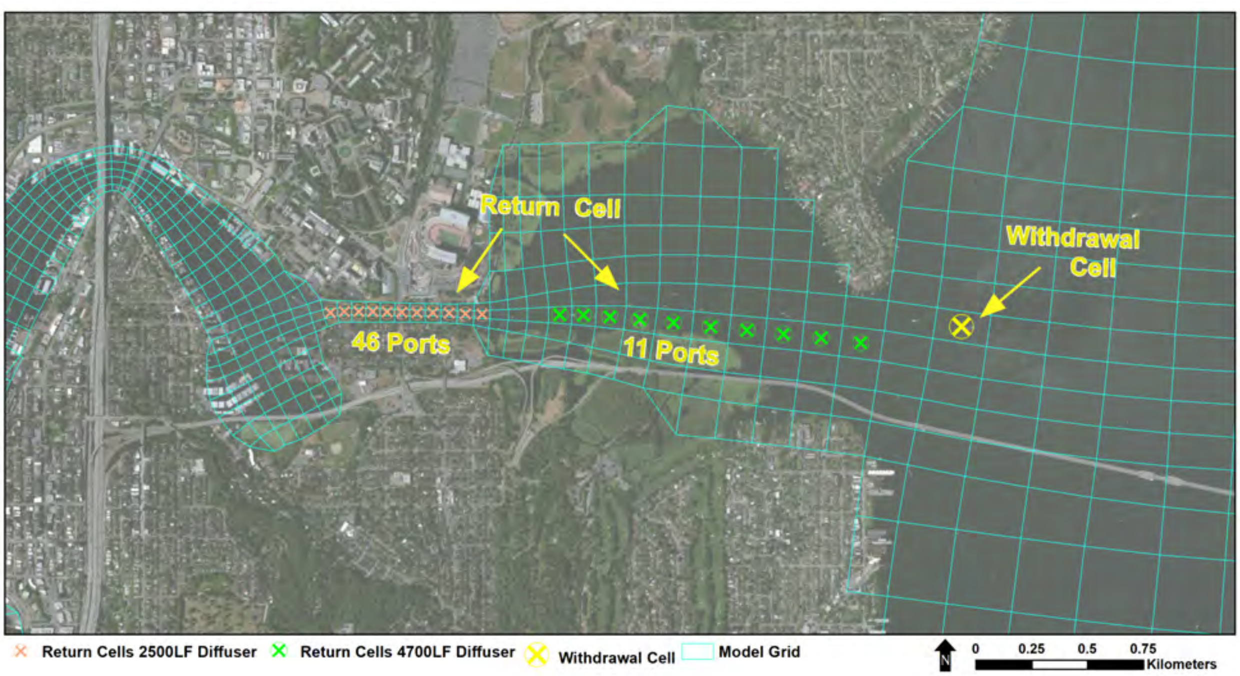

Figure 7.3: Scenario 1B implementation.

7.4 Scenario 2 Configuration

The second scenario closely resembles scenario 1B, with the key distinction being an increase in the volume of water transferred from Lake Washington into the lower section of Montlake Cut. Similar to scenario 1B, the implementation of scenario 2 uses the Jet/Plume boundary condition and follows a withdrawal return flow approach. However, in this case, a substantial increase is observed as 300 cfs of cold water from Lake Washington is transferred through the diffusers in Montlake Cut. This volume triples the flow rate compared to scenario 1B while maintaining the same delivery method.

7.5 Scenario 3 Configuration

The third scenario incorporates an innovative solution by introducing diffusers along a 2,500 ft long line in the Fremont Cut. This approach offers an alternative method for injecting additional water into the ship canal, resulting in effective temperature reduction measures. Additionally, the length of the section where the diffusers are located along the Montlake Cut is extended to cover a distance of 5,000 ft, extending into Portage Bay. Unlike the previous scenario, where a single large pipe was used to transfer 300 cfs of water simultaneously, this scenario adopts a more distributed strategy. Specifically, 200 cfs of cold water from Lake Washington is pumped through the diffusers in the Montlake Cut, while an additional 100 cfs of cold water from Lake Washington is pumped through the diffusers in the Fremont Cut. This configuration allows for a comprehensive examination of the impact of diffuser location on the overall results. By exploring the influence of diffuser placement, valuable insights can be gained regarding its effect on temperature reduction along the ship canal. Figures 7.4, 7.5, and 7.6 show the plan from Jacobs for Scenario 3. Scenario 3 was implemented using a Jet/Plume boundary condition, which employed a withdrawal return flow approach. This approach is similar to the methodology employed in scenarios 1B and 2. An overview of all three flow scenarios is provided in Table 7.1.

It's important to note that all scenarios incorporate a bottom barrier at the upstream end of Montlake Cut, in accordance with the specifications outlined by Jacobs' designs. This element is absent from the baseline model, as it does not reflect the present conditions.

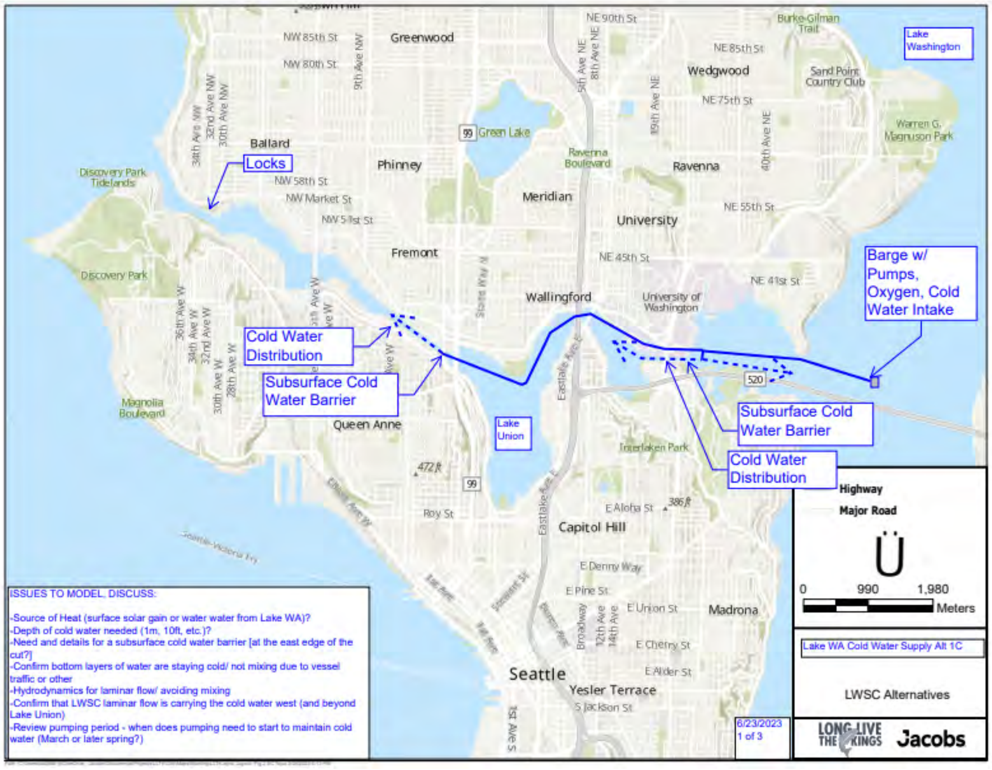

Figure 7.4: Scenario 3 from Jacobs.

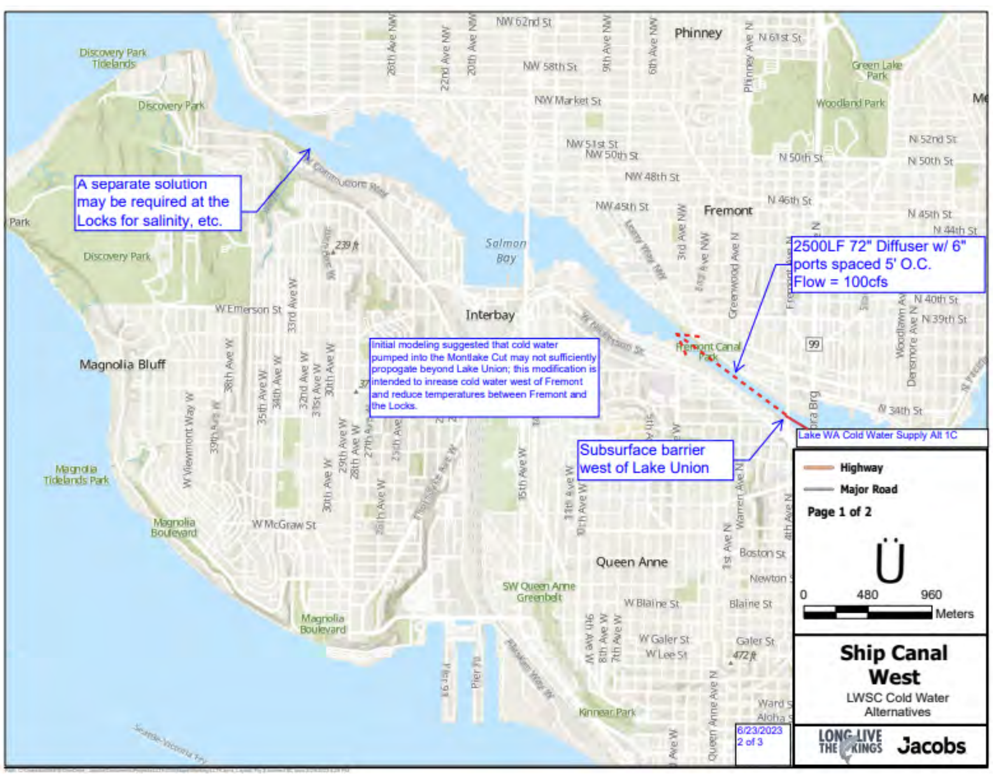

Figure 7.5: Scenario 3 from Jacobs (close-up of western portion).

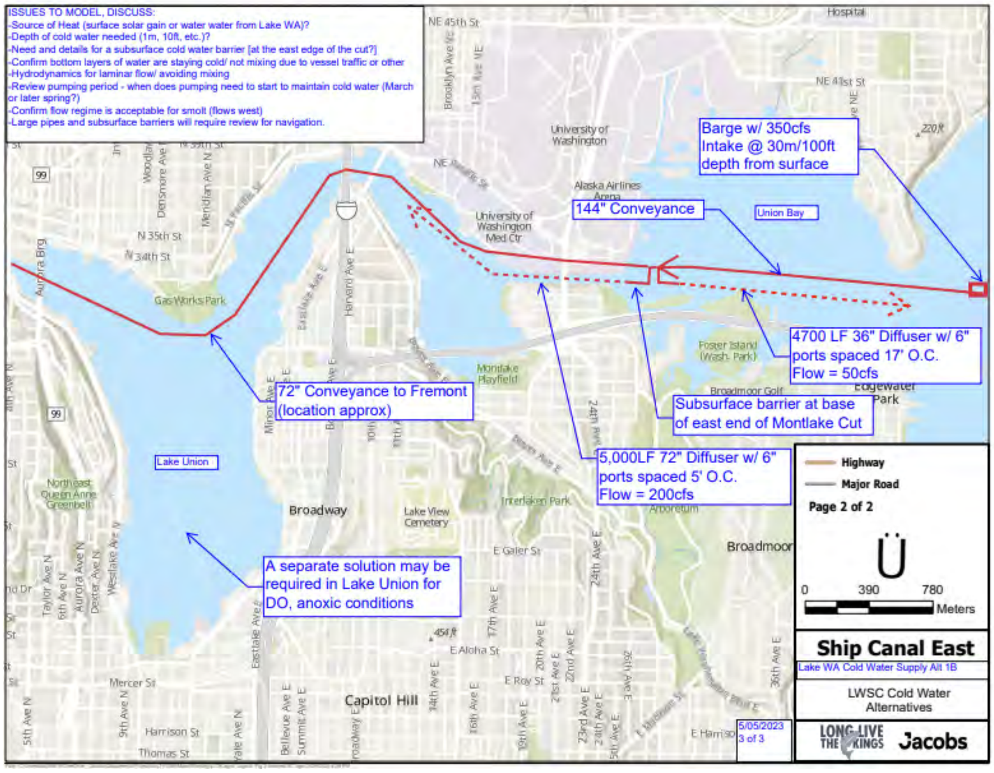

Figure 7.6: Scenario 3 from Jacobs (close-up of eastern portion).

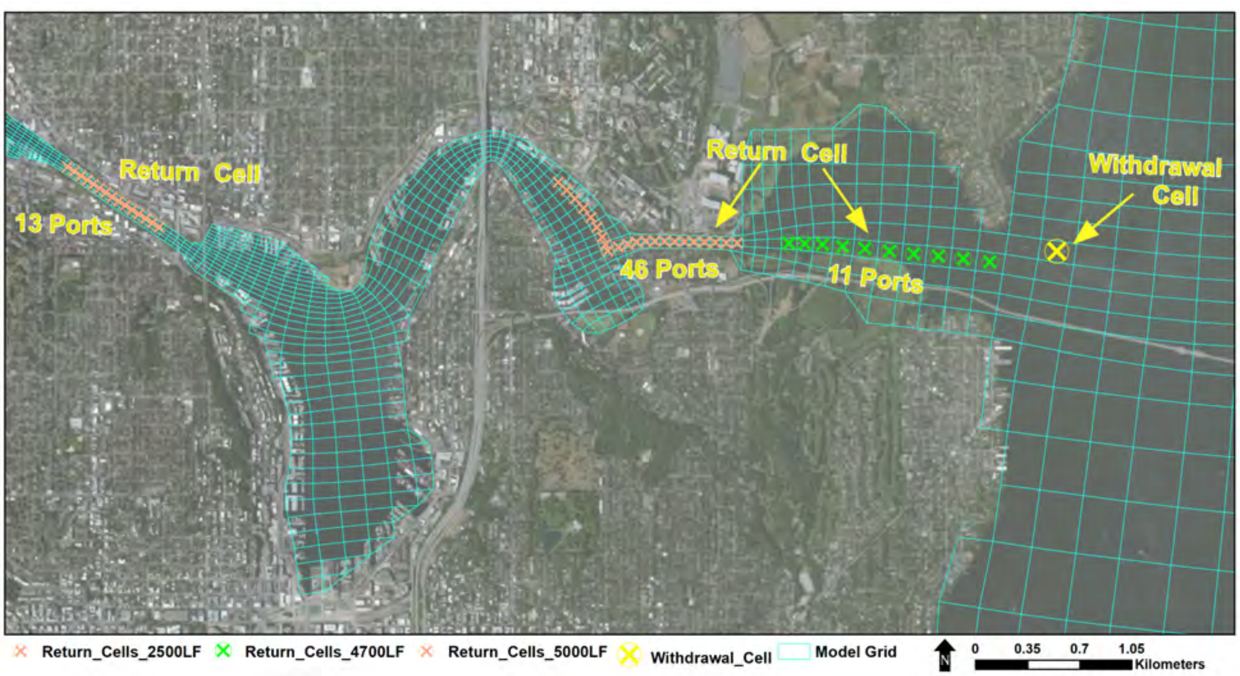

Figure 7.7: Scenario 3 implementation.

Table 7.1: Scenarios summary.

Model Scenario	East of Montlake Bridge	West of Montlake Bridge	West of Fremont Bridge	Total flow West of Montlake Bridge	Total Pumped Flow	Pct. of Total LWSC Discharge (25th Pct.; 405 cfs)
1B	25	100	0	100	125	30%
2	50	300	0	300	350	86%
3	50	200	100	300	350	86%

7.6 Results and Discussion

7.6.1 Temperature Results

The simulation period was from January 2018 to January 2021. After the simulations were completed, the baseline and the three scenario model results were compared for temperature at some stations to illustrate the scenario's effectiveness. A time series of temperature differences between the baseline and Scenario 1B models were extracted. A comparison of water temperatures at several station locations was performed.

Water temperature is a primary determinant of salmon health, development, migration, and survival. Heat-stressed salmon face increased risks from parasites, infection, predation, and migration blockages or delays which can result in increased mortality rates and reduced spawning success (Urgenson, Kudo, and DeGasperi, 2021). Several temperature milestones have been established based on the Synthesis Report prepared by King County WRIA8.

- Lethal Conditions per King County Synthesis Report: 22° C
- Temperature Allowing Fish Passage Based on Tracking Data: 19° C
- Temperature Required for Salmonid Rearing and Migration Only: 17.5° C
- Core Temperature Summer Salmonid Habitat: 16° C

These temperature milestones are specified in the temperature comparison figures presented in Appendix C (Figure C.1 to Figure C.18). In these comparison figures, the red line shows the observed data, the blue line shows the baseline model results and the green line shows the scenario run results. For the Fremont Bridge, the results of scenario 3 are as effective as scenario 2 (Figures C.8 and C.9). The reason is that although Scenario 2 involves a notably larger flow rate at Montlake, the cumulative flow rates across Scenarios 2 and 3 remain similar. When considering the outcomes, it becomes evident that the diffusers in Fremont Cut within scenario 3 are effectively engaging with the salt wedge. This interaction reduces salinity levels extending further upstream within the ship canal. Through the exclusion of saline water from Lake Union, the colder water released from the Montlake Cut diffusers in Scenario 3 is more prone to settling at the base of Lake Union due to lower salinity concentrations in the hypolimnion, as observed in Scenario 2 where salinity infiltrates Lake Union to a greater degree.

Based on the findings presented in Tables C.1 to C.18, all the scenarios investigated in this study demonstrate a reduction in the number of days where the temperature exceeds the specified limit. Thus, these scenarios would be particularly effective in mitigating temperatures surpassing the lethal limit and hindering fish passage during the critical months of May through September.

Among the scenarios examined, Scenario 3 proved to be the most effective in reducing these temperature thresholds, however, it seems likely that a similar effect might be achievable with less for, or a different distribution between diffuser groups. This can be attributed to the higher volume of water being pumped into the bottom of Montlake Cut, which results in a more substantial decrease in the number of days with excessive temperatures.

A comparison between Scenario 2 and Scenario 3 reveals that Scenario 3 performs better in reducing temperature thresholds at the University Bridge, Fremont Bridge (at a depth of 40 ft), and Ballard Bridge stations. However, at the Gas Works Park station, Scenario 2 demonstrates greater effectiveness, while Scenario 1B and Scenario 3 yield similar results.

These observations highlight the varying effectiveness of the scenarios across different monitoring stations, suggesting the influence of specific site characteristics. Further analysis and evaluation of these variations would be beneficial for a more comprehensive understanding of the scenarios' impacts. Figure 7.9 shows the temperature vertical profile along the LWSC line shown in Figure 7.8 on August 20, 2019 at 3:30 pm. Figures 7.10, 7.11, and 7.12 show the temperature difference between the baseline and scenarios 1B, 2, and 3, respectively. As can be seen, there is a temperature reduction more significant than 3°C at some locations in all scenarios. However, in scenarios 2 and 3, the reduction in temperature is more extensive and noticeable, extending to the Ballard Bridge and Large Lock stations. This cooling effect is evident even in shallower cells, setting it apart from the changes observed in scenario 1B at this specific date and time. These more extensive temperature changes are not because of an accumulation of freshwater from the diffusers (see the discussion in the following section), but rather, these temperature reductions occur due to water temperature changes due to salt wedge intrusion limitations in addition to the freshwater supplemented from the diffusers.

Figure 7.8: 2DH plan view map showing the line along LWSC in which the vertical profiles are extracted.

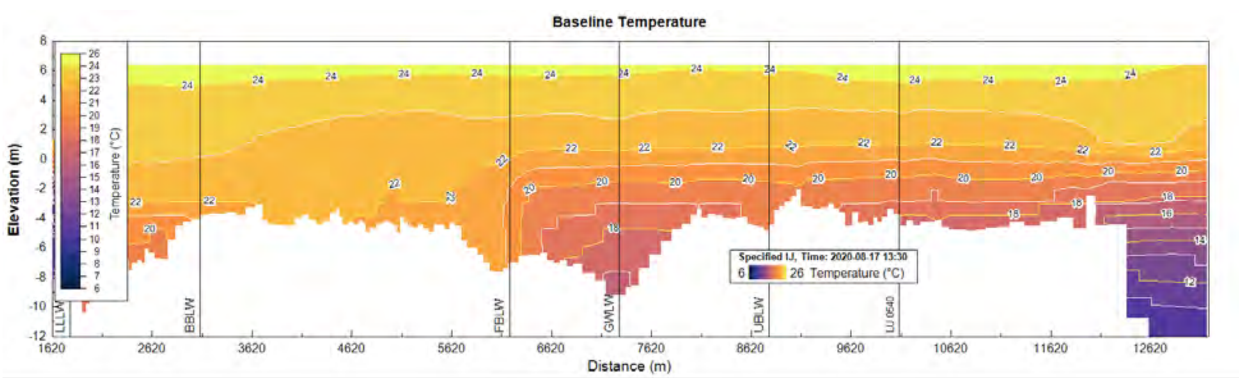

Figure 7.9: Baseline model temperature vertical profile along LWSC line.

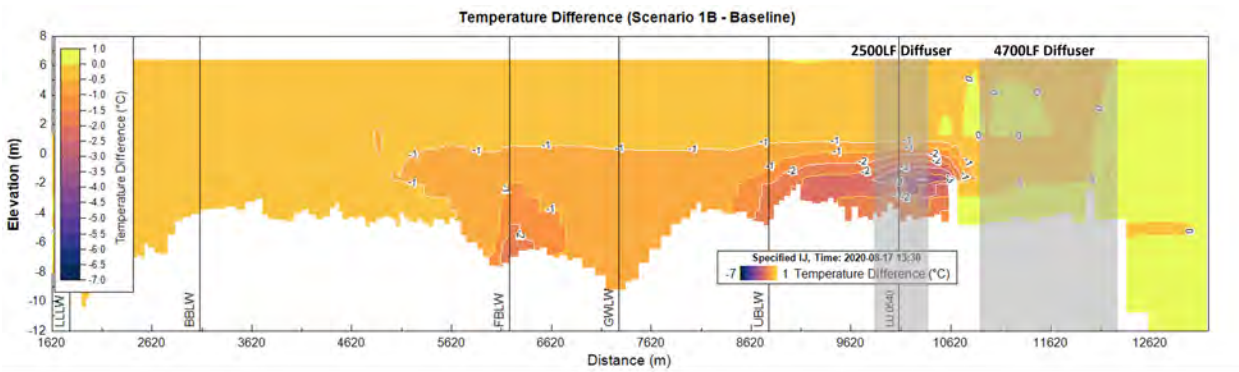

Figure 7.10: Vertical profile temperature difference between the baseline and scenario 1B model along LWSC line.

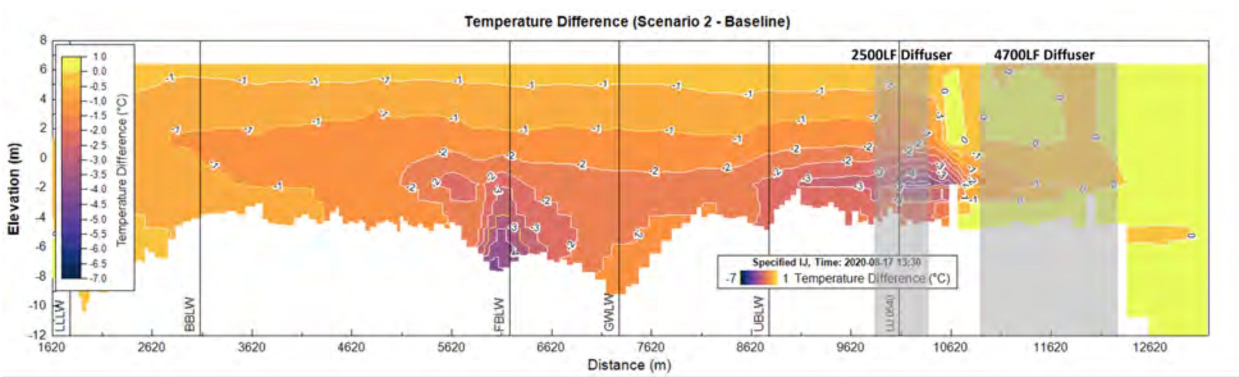

Figure 7.11: Vertical profile temperature difference between the baseline and scenario 2 model along LWSC line.

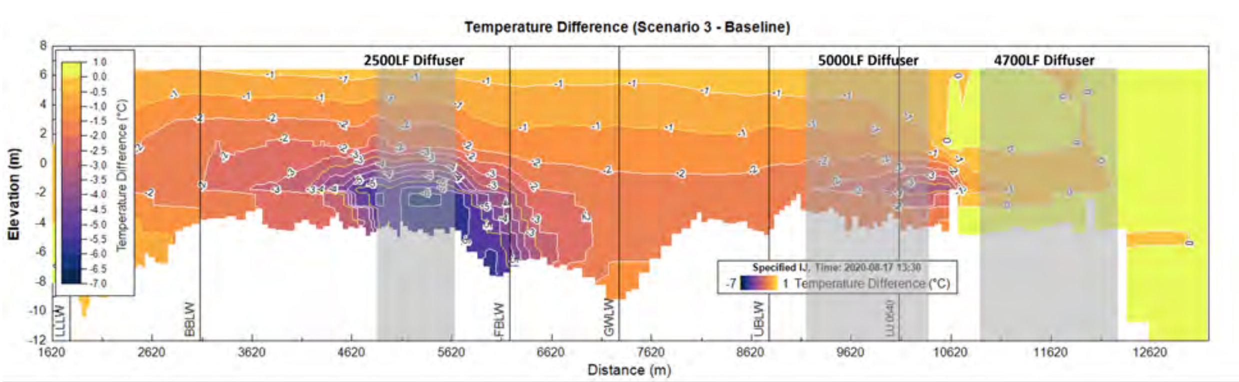

Figure 7.12: Vertical profile temperature difference between the baseline and scenario 3 model along LWSC

In conclusion, the results demonstrate that all scenarios lead to a reduction in the number of days with temperatures above the specified limits, with Scenario 2 being the most effective overall. However, the effectiveness of the scenarios can vary across different monitoring stations, indicating the need for site-specific considerations when implementing mitigation measures.

7.6.2 Salinity Results

The simulation was conducted over the period from January 2018 to January 2021. Following the completion of the simulations, the results of the Baseline, Scenario 1B, Scenario 2, and Scenario 3 models were compared at various validation stations to assess the salinity levels. The water salinity was examined at multiple station locations, including the University Bridge at depths of 21 ft and 35 ft, Gas Works Park at depths of 25 ft and 36 ft, the Fremont Bridge at depths of 31 ft and 40 ft, the Ballard Bridge at depths of 21 ft and 32 ft, and the Large Lock at depths of 18 ft, 28 ft, and 43 ft. The salinity levels were compared, and the corresponding plots are depicted in Figures C.19 to C.51.

In verbal comments from the USACE, it was stated that dramatic sudden changes in the salinity concentrations observed at some stations are most likely a consequence of saltwater drain failures at the Ballard Locks. The saltwater drain and flow rate conditions are poorly understood, and little data exists to support direct parameterization in the LWSC model. The sudden observed change in salinity we see at some stations in the plots below often reflects the first indication, in real-time, of a saltwater drain failure. Note that the USACE typically reduces the usage of the large locks (to the extent possible) until salinity concentrations in the ship canal recover. In the present model, we considered both the flow rate and the condition of the saltwater drain as a point of great uncertainty, which we intend to investigate further in collaboration with stakeholders and partners.

Acknowledging the considerable challenge of accurately simulating salinity in systems with concentrations below 1 ppt is essential. Density differences in water from small changes in salinity concentration represent an extremely large change compared to changes in freshwater due to temperature alone. Therefore, even small concentrations of salinity in an otherwise freshwater environment represent a substantial component contributing to intense seasonal stratification, potential declines in hypolimnetic dissolved oxygen, and increased stress and mortality for aquatic life beyond salmon alone.

However, since salmon are anadromous and thus insensitive to salinity, the acceptable results obtained in this regard can be deemed satisfactory. Still, they should be considered an area for further improvement due to the importance of salinity in driving vertical mixing in the LWSC.

A key regulatory limit dictates that salinity levels should not exceed 1 ppt at the University Bridge station. Still, salinity concentrations can routinely exceed this level further downstream, especially during late summer, when the salt wedge is generally the largest. In the model simulations, the salinity concentrations remained relatively unchanged in most stations. However, the results at the Fremont Bridge show evidence of the beneficial effects of cold water supplementation for reducing salt intrusion at this location, such as in Scenario 3. Due to the relatively large difference in density, it is somewhat surprising that cold fresh water could produce such an effect, even at a rate of around 100 cfs. However, using 6-inch diffusers along the bottom of the channel oriented toward the surface produces a small upward motion where the motion of the salt wedge might otherwise be unimpeded. This additional momentum, driving convective mixing within the otherwise calm hypolimnetic waters, causes saltwater to mix upward, producing static instability in the water column before the saltwater sinks again.

Further analysis was done show the effect of three scenarios on the salinity. Figure 7.13 shows the salinity vertical profile along the LWSC line shown in Figure 7.8 on August 20, 2019 at 3:30 pm. Figures 7.14, 7.15, and 7.16 show the salinity difference between the baseline and scenario 1B, 2, and 3 respectively. In all scenarios, the figures highlight a salinity reduction of up to 2 ppt at a few locations near the Large Lock station. However, in scenarios 2 and 3, the area with reduced salinity is notably larger than in scenario 1B at this specific date and time. Comparing scenarios 2 and 3, the primary outcome we observe is the potential to reduce saltwater intrusion into the ship canal effectively. In Scenario 3, it is evident that the introduction of diffusers in Fremont Cut has effectively halted the advancement of the salt wedge beyond the Fremont Bridge, preventing its entry into Lake Union. This fundamental distinction from Scenario 2 has led to a more significant accumulation of fresh water settling at the bottom of Lake Union instead of dispersing across the more saline waters in the Lake Union hypolimnion and flowing downstream more efficiently. This contrasts with the behavior observed in Scenario 3, where the freshwater appears to dive downward into the deeper layers of Lake Union.

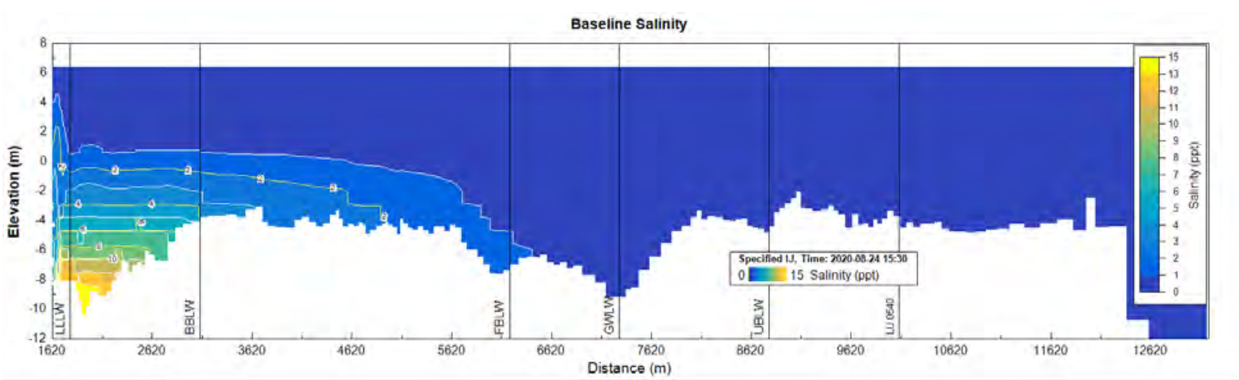

Figure 7.13: Baseline model salinity vertical profile along LWSC line

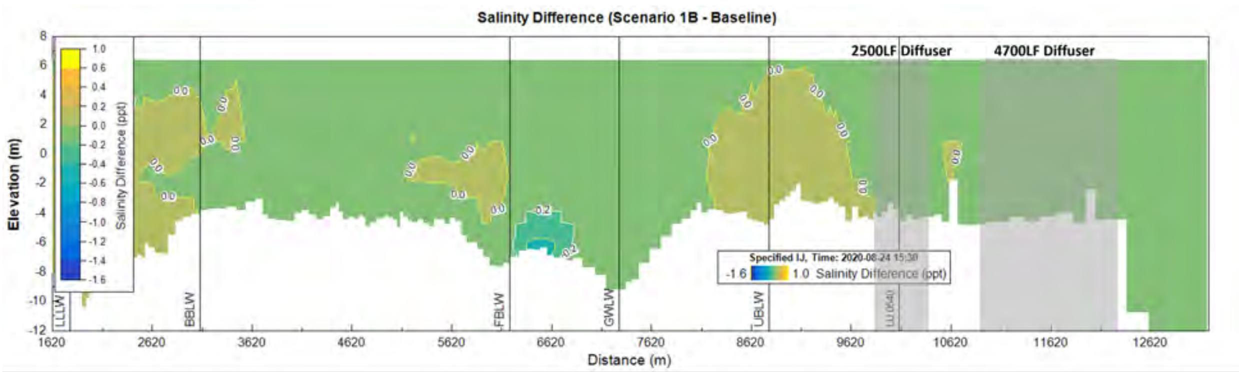

Figure 7.14: Vertical profile salinity difference between the baseline and scenario 1B model along LWSC line

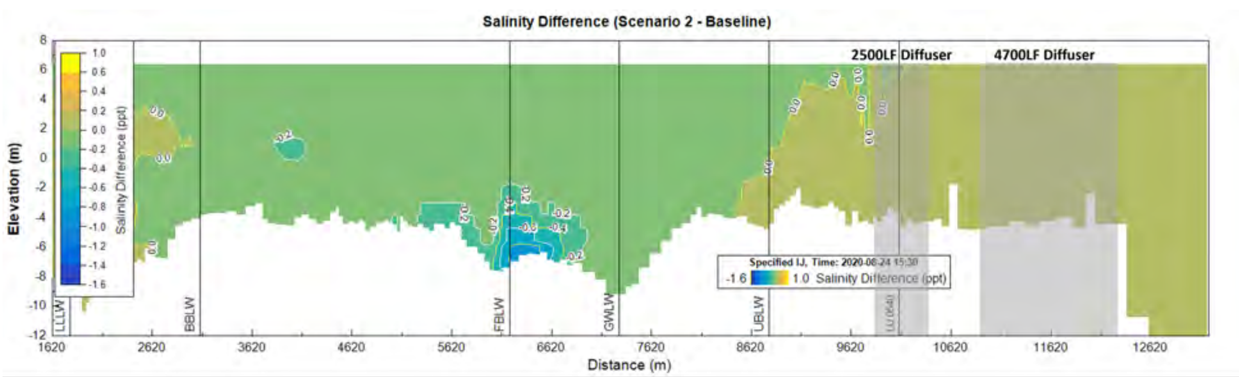

Figure 7.15: Vertical profile salinity difference between the baseline and scenario 2 model along LWSC line

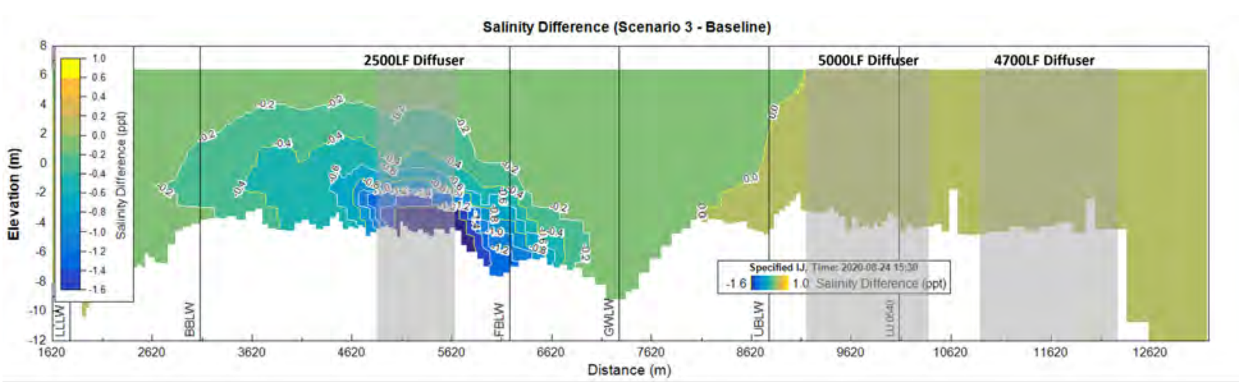

Figure 7.16: Vertical profile salinity difference between the baseline and scenario 3 model along LWSC line

These improvements resulted in notable reductions in the resistance to mixing within the ship canal. Based on the salinity comparison figures, it is evident that Scenario 1B had minimal impact on the salinity levels. Still, Scenario 2 and, more notably, Scenario 3 demonstrated significant reductions in salinity, with some stations showing up to a 1 ppt decrease in salinity levels.

7.6.3 Discussion

The simulation showed Scenario 1B implementation as successful, yielding favorable outcomes. Cold-water supplementation in Montlake Cut effectively reduced temperatures through the middle-deeper water layers. Temperatures can be reduced by 1-2 degrees Celsius locally near the diffusers, especially in summer. The occurrence of near-lethal temperatures for salmon can be effectively reduced using this scenario. However, it should be noted that the degree of cooling below critical thresholds in deeper waters presents a less conclusive picture due to the under-prediction of mixed-layer thickness in certain areas and the over-prediction of deep temperatures during summer at the deepest Fremont Bridge and Gas Works Park stations.

In the case of Scenario 2, where 300 cfs of water was pumped from Lake Washington into the bottom of Montlake Cut, the simulation showed a more pronounced temperature reduction, reaching up to 5 degrees Celsius near the diffusers, as anticipated.

The Scenario 3 simulation, on the other hand, surpassed Scenario 2 in terms of temperature reduction effectiveness at most stations, especially at the Ballard Bridge station, which is situated near the Locks.

To assess the impact of cold water pumping in the three scenarios, a dye tracer was employed by introducing 100 mg/l of dye into the flow of each set of diffusers. The dye tracer allows us to visualize the movement of the cold water. As indicated in Figure 7.17, three cross sections were chosen for analysis. These cross sections include the NS cut and EW cut, which represent north-south and east-west directions, respectively, across Lake Union. Additionally, the LWSC line, previously used to examine salinity and temperature differences between scenario models and the baseline model, was also employed for further investigation.

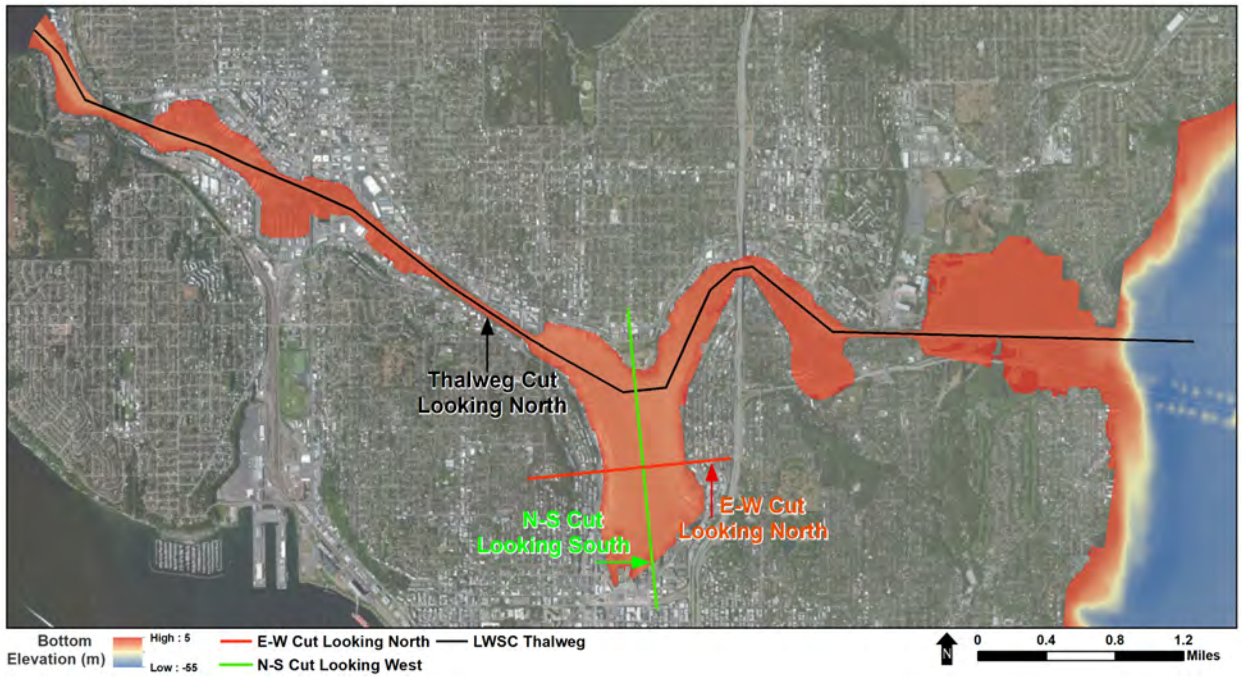

Figure 7.17: 2DH dye analysis cross section lines

The movement of cold water as a plume can be observed in all three scenarios, as depicted in the NS cut and LWSC cut vertical profile dye concentration figures. Additionally, the EW cut Figures illustrate the distribution of dye at various depths in Lake Union with higher dye concentrations at the bottom of the lake, with scenario 2 having the highest dye concentration along this profile, as expected. In scenario 2, the cold water plume appears larger than in scenario 1B, which can be attributed to the increased water pumping. A distinct pattern for the dye is observed in scenario 3, as shown in Figure 7.26. This pattern is closely related to the restricted salt wedge between Ballard Bridge and Fremont Bridge. As a result of the absence of salinity, the cool water released from the diffusers tends to fill up the bottom of the lake.

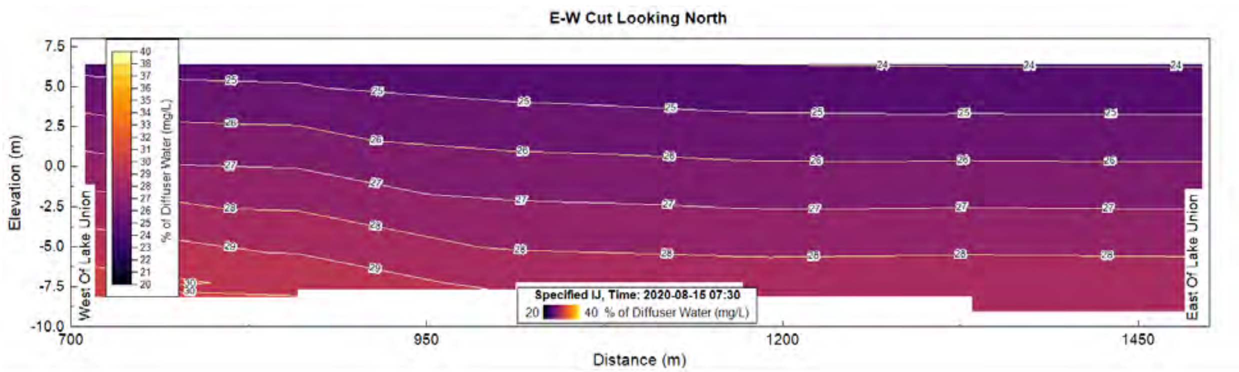

Figure 7.18: Dye tracer concentration along the EW cut in Scenario 1B

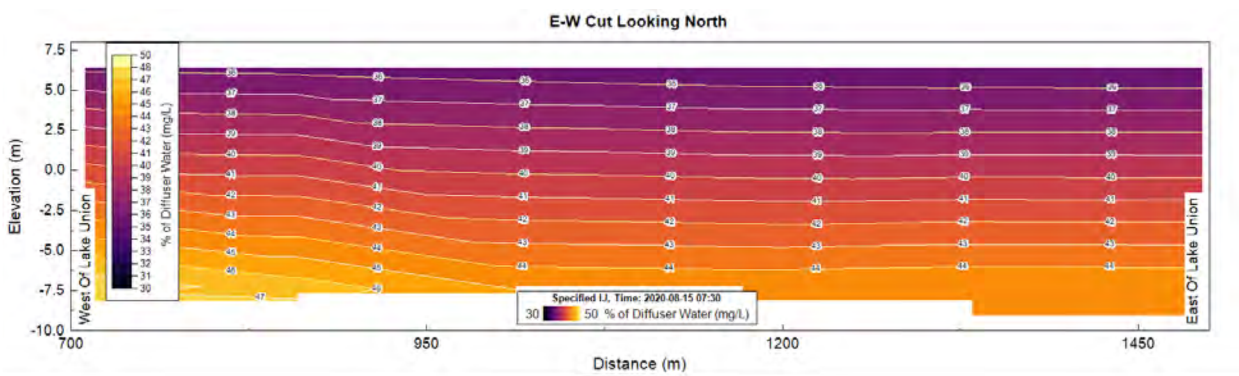

Figure 7.19: Dye tracer concentration along the EW cut in Scenario 2

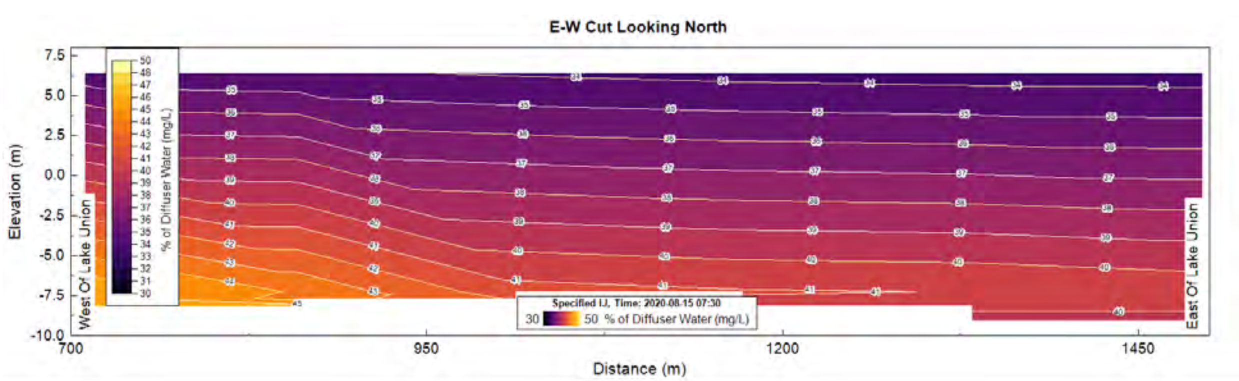

Figure 7.20: Dye tracer concentration along the EW cut in Scenario 3

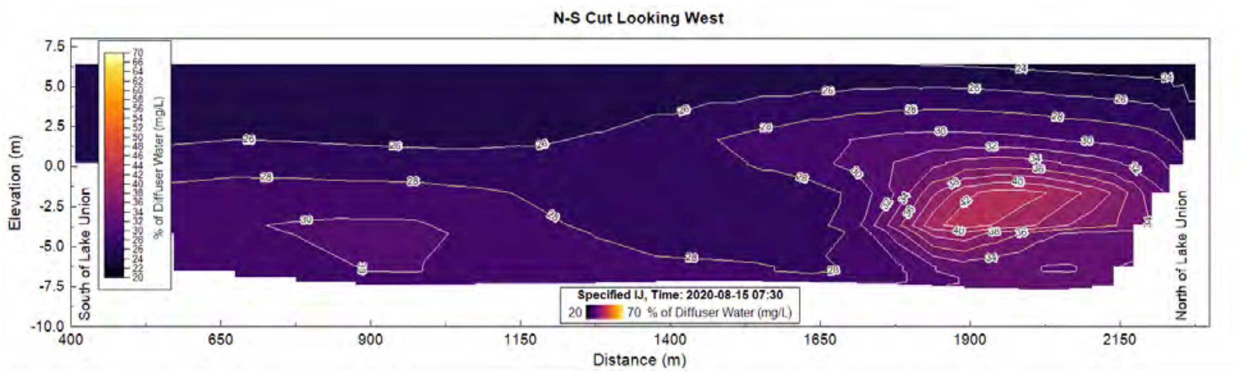

Figure 7.21: Dye tracer concentration along the NS cut in Scenario 1B

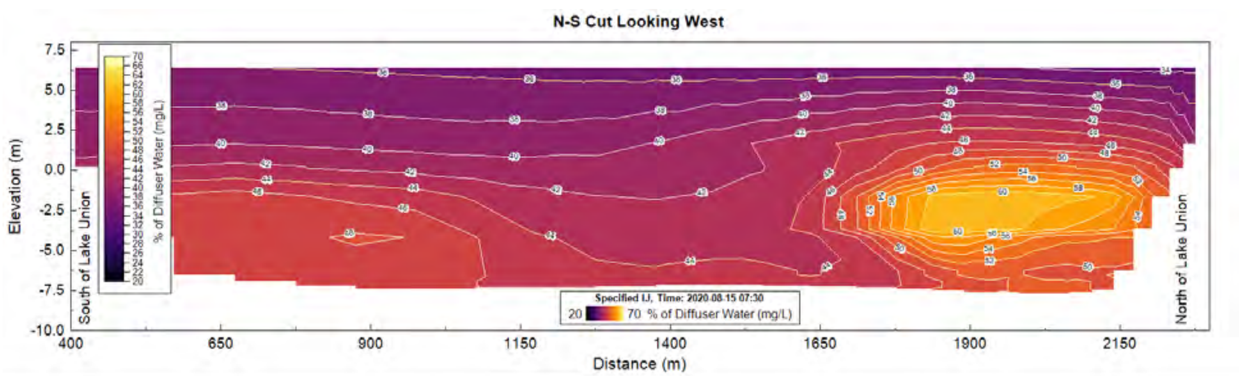

Figure 7.22: Dye tracer concentration along the NS cut in Scenario 2

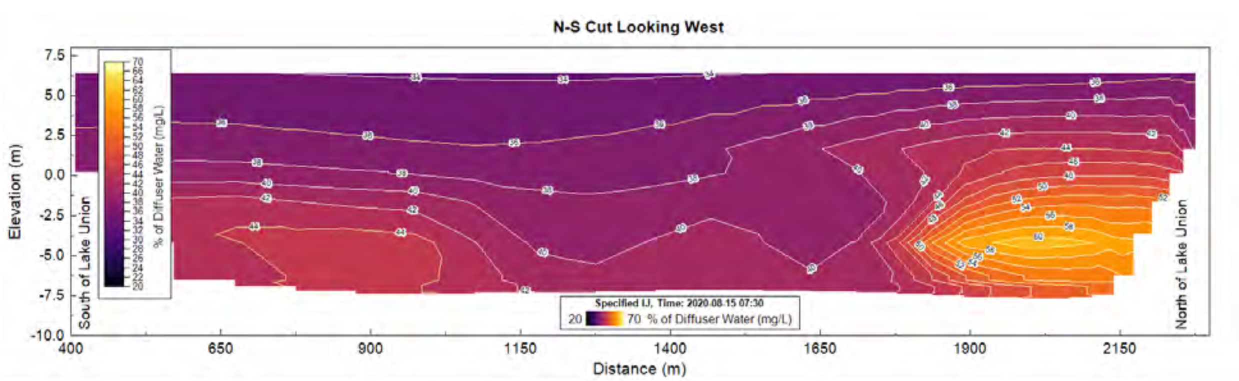

Figure 7.23: Dye tracer concentration along the NS cut in Scenario 3

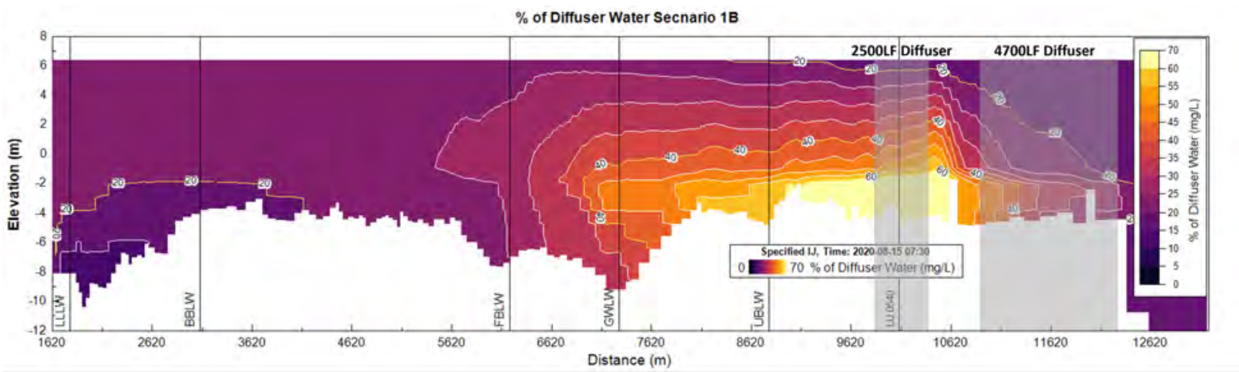

Figure 7.24: Dye tracer concentration along the LWSC cut in Scenario 1B

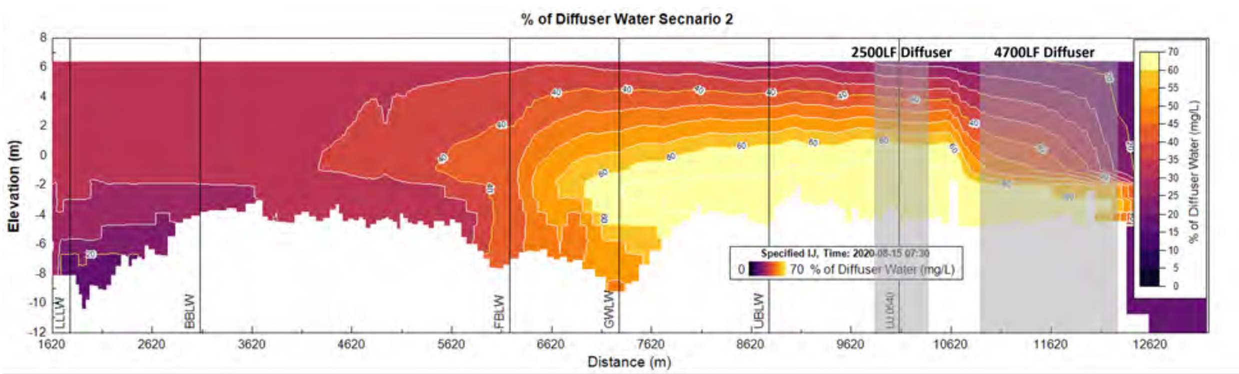

Figure 7.25: Dye tracer concentration along the LWSC cut in Scenario 2

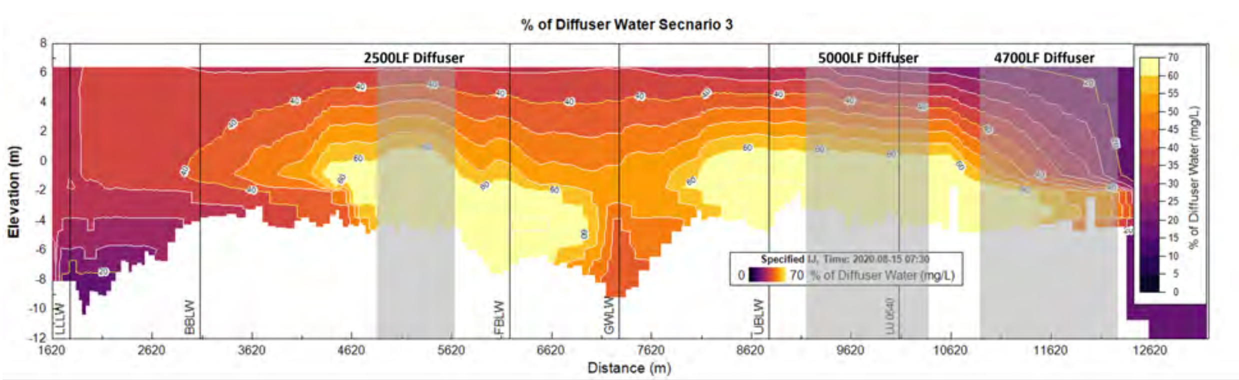

Figure 7.26: Dye tracer concentration along the LWSC cut in Scenario 3

8 STUDY SUMMARY

8.1 Summary of the Baseline Model

This study configured a hydrodynamic model to simulate the complex dynamics of Lake Washington, Lake Union, and the LWSC.

The model's performance was assessed over a continuous three-year period from January 2018 to January 2021, focusing on its ability to simulate water surface elevation, temperature, and salinity accurately. Remarkably, the model performed excellently in replicating observed water surface elevations during this time. Furthermore, given the significant complexity of modeling salt wedge intrusion in the LWSC, it accurately simulated salinity patterns to a reasonable degree of certainty. However, the salinity results appear unsatisfactory at a few stations due to low measured salinity concentrations. Generally, this can be explained by a lack of instrument precision at low concentrations (*i.e.*, there are limitations to the observational data at these stations, which impact model-data comparison). It also showed excellent temperature results except for a few stations, at which it still maintained an acceptable level of performance in terms of temperature simulations.

To ensure reliability, the model underwent extensive calibration and validation processes, solidifying its credibility and effectiveness in capturing the intricate hydrodynamic behavior of the studied water systems.

8.1.1 Future Improvements

While the model captured many aspects of the LWSC successfully, several areas of potential improvement were identified for future studies.

1. Develop more precise layering for the LWSC to capture the salinity transition more accurately.
2. Add water quality predictions to the model, allowing for water clarity and temperature feedback due to seasonal clarity changes.
3. Implement a more robust method for lock exchange simulation by automatically adjusting the flow rate into/out of the changes based on water level differences.

4. Improve the overall efficiency of the model and reduce run times.
5. Evaluate vessel-driven motion's potential impact on LWSC stratification.

8.2 Summary of Scenario Models

Scenarios 1B, 2, and 3 were implemented to simulate a system that supplements cold water in the LWSC. The plan is for cold water to pump into the bottom of the Montlake Cut, enabling it to flow downstream into the ship canal. The results demonstrate the successful implementation of the scenarios, indicating that introducing cold-water supplementation in Montlake Cut effectively reduces temperatures within the middle to deeper water layers. In the vicinity of the diffusers, particularly during the summer, local temperatures can be effectively lowered by as much as 1 degree Celsius in scenario 1B. In scenarios 2 and 3, the increased flow rate resulted in more significant temperature reductions, and a more substantial pathway of freshwater from the diffusers was evidence (see Figures 7.25 and 7.26). Consequently, both scenarios exhibit greater effectiveness in reducing temperatures than scenario 1B, where a lower flow rate was employed. The temperature reduction in all scenarios effectively mitigates temperatures detrimental or potentially lethal to salmon life.

8.2.1 Future Scenario Improvements

In addition to potential improvements to the model itself, other scenarios could also be analyzed. These could include:

1. Incorporating alternative or additional diffuser stations in other locations, such as Near Gas Works Park, Fisherman's Terminal, or SPU.
2. Further refinement of diffuser placement, configuration, or depth to produce a better-optimized design to reduce the required flow rate while sustaining decreased temperatures during critical migration periods.

Additional approaches to consider for reducing water temperatures or promoting increased mixing during the summer months include could alternative concepts such as:

1. Providing additional shoreline shading/protection.
2. Changes in lockage patterns or additional mitigation at locks to prevent salinity intrusion because salinity increases the energy necessary for mixing forces to overcome a stably stratified water body. This might be achieved by implementing bubble barriers or pre-fill flushing of the lock chambers to reduce the exchange of salt and freshwater during lock operations.

Finally, the saltwater drain's flow rate remains a critical area of uncertainty contributing to the overall loading of saltwater into the LWSC. Analysis performed by the Muckleshoot Tribe suggests that the function of the saltwater drain can be evaluated using historical data. Still, a predictive approach or one based on present conditions is lacking. Future improvements to the model could include evaluating historical data to understand better the likelihood of a saltwater drain failure, which would be critical in capturing several significant increases in salinity, most commonly associated with saltwater drain failures.

8.3 Potential Impacts on the Thermal Structure of Lake Washington

Concerns about the impacts of a substantial hypolimnetic water withdrawal on the thermal structure of Lake Washington must be evaluated adequately to ensure that the proposed solutions will not pose a detrimental impact on temperature and water quality. This section will provide a brief discussion of the methodology and findings regarding impacts to the thermal structure of Lake Washington due to the various proposed withdrawal scenarios.

A simple and effective way to evaluate potential impacts is to compare vertical temperature profiles from the withdrawal cell. For example, suppose first that the withdrawal significantly impacted Lake Washington; we would anticipate an evident change in the vertical profile, specifically during peak summer periods. Most likely, we would observe a reduction in the overall thickness of the hypolimnion due to cold water withdrawal. However, if we suppose that the withdrawal has little or no impact, we might anticipate very little difference during the summer period and little to no change in the relative thickness of the epilimnion and hypolimnion. Figure 8.1 provides a snapshot of the vertical temperature profile from the withdrawal location for the Baseline and Scenario Models. Each symbol represents the temperature at a vertical model grid cell.

Based on Figure 8.1, only minor differences in the temperature profiles can be observed. These differences are much less than 1 degree C for most of the water column, and only minor deviations are notable between 6 and 16 meters in depth. The mixed layer depth and hypolimnetic temperatures show little to no impact from the withdrawal. Broadly, this could be related to the annual mixing cycle of Lake Washington (monomictic), generally cool weather conditions during winter (allowing significant heat exchange with the atmosphere), and relatively low residence time (generally 2-8 years based on the interquartile range of discharge from the Ballard Locks). While the withdrawal is large relative to low flow conditions through the LWSC, it generally represents a much smaller portion of the average discharge. Also, these low-flow conditions occur for a relatively short period, and any cold water supplementation above the specified outflow from the Ballard Locks would result in more diffuser water flowing back into Lake Washington. In addition to the low residence time and relatively large volume of Lake Washington, this means that the withdrawal is generally not significant enough to produce any meaningful impact on the thermal structure of Lake Washington. That said, any potential reductions in the average flow or anticipated inflow characteristics of the Lake Washington-Cedar-Sammamish Watershed should prompt a re-evaluation of the potential impacts of any large withdrawal, as we evaluated in this study.

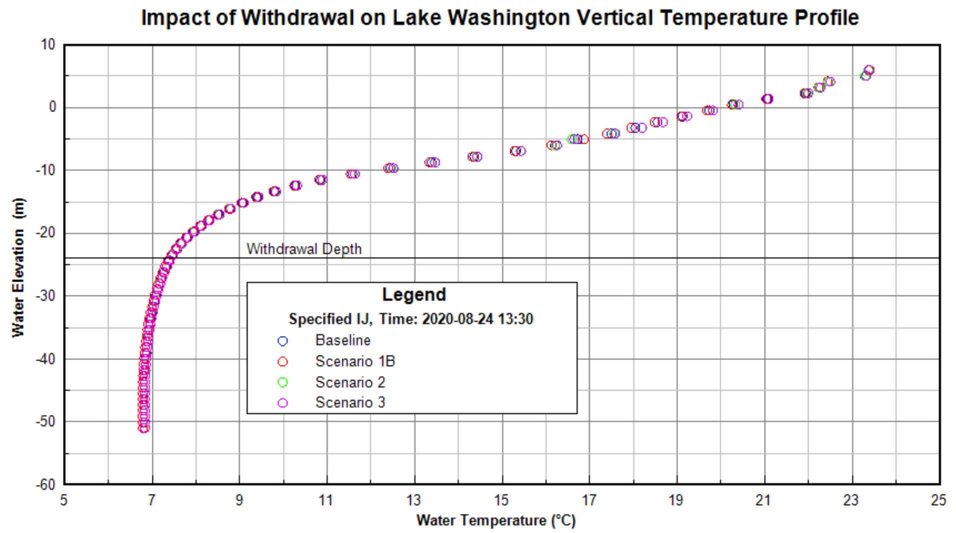

Figure 8.1: Comparison of Baseline and Scenario Model vertical temperature profiles near the withdrawal cell.

9 KEY FINDINGS

The key takeaway of this study can be summarized as follows:

1. DSI has developed a hydrodynamic model that simulates the complex dynamics of Lake Washington, Lake Union, and the LWSC in this project.

2. The model's performance was evaluated over three years (January 2018 to January 2021), focusing on accurately simulating water surface elevation, temperature, and salinity.

3. The model demonstrated excellent performance in replicating observed water surface elevations, with a maximum absolute error of 7.5 cm during the study period.

4. Overall, the model exhibited excellent accuracy in simulating salinity patterns, with all but one station demonstrating good or excellent model performance. However, some stations presented challenges due to extremely low measured salinity concentrations, and substantial improvements in model simulations of salinity could be possible if a better understanding of the saltwater drain could be used to improve the model parameterization for that feature of the Ballard Locks.

5. Overall, the model achieved excellent temperature results across the model, with a root mean square error of less than 1 °C, and skill scores in excess of 0.9 with only a few stations showing a minor deviation from expected performance.

6. Extensive calibration and validation are still needed to ensure the model's reliability and effectiveness in capturing the complex hydrodynamic behavior of the studied water systems.

7. High temperatures in the LWSC result from solar energy heating the surface of Lake Washington, thus increasing the strength of stratification and preventing ventilation of hypolimnion waters. During the summer, this contributes to seasonal anoxia and increases biological stress for migrating salmon (*i.e.*, waters are too hot or have insufficient dissolved oxygen to support respiration). This ultimately contributes to increased mortality for spawning salmon and reduces the overall survivability of species that rely on the Lake Washington-Cedar-Sammamish watershed for spawning habitat.

8. Scenarios 1B, 2, and 3 were implemented to simulate a system introducing cold-water supplementation in the Montlake Cut, which then flows downstream into the ship canal.

9. The results demonstrated the successful implementation of the scenarios, effectively reducing temperatures in the middle to deeper water layers.

10. In the vicinity of the diffusers, particularly during the summer season, scenarios 1B, 2, and 3 successfully lowered local temperatures by more than 2 degrees Celsius. Greater reductions in temperature could occur due to salt wedge mitigation.

11. Scenarios 2 and 3, with increased water pumping, achieved greater temperature reductions than Scenario 1B, which had a lower flow rate.

12. The temperature reductions in these scenarios significantly would mitigate potentially harmful or lethal temperatures for salmon life in the LWSC.

13. It is unlikely that the proposed withdrawals from Lake Washington would create long- or short-term impacts on the thermal structure of the larger water body. This was generally due to the large volume of Lake Washington, a reliable annual cycle of mixing and cooling, and low residence time overwhelm any impacts that could be expected from withdrawals from the hypolimnion of the described size (up to approximately 350 cfs).

Part I

References and Appendices

10 REFERENCES

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A CALIBRATION OVERVIEWS FOR SELECTED STATION

A.1 University Bridge

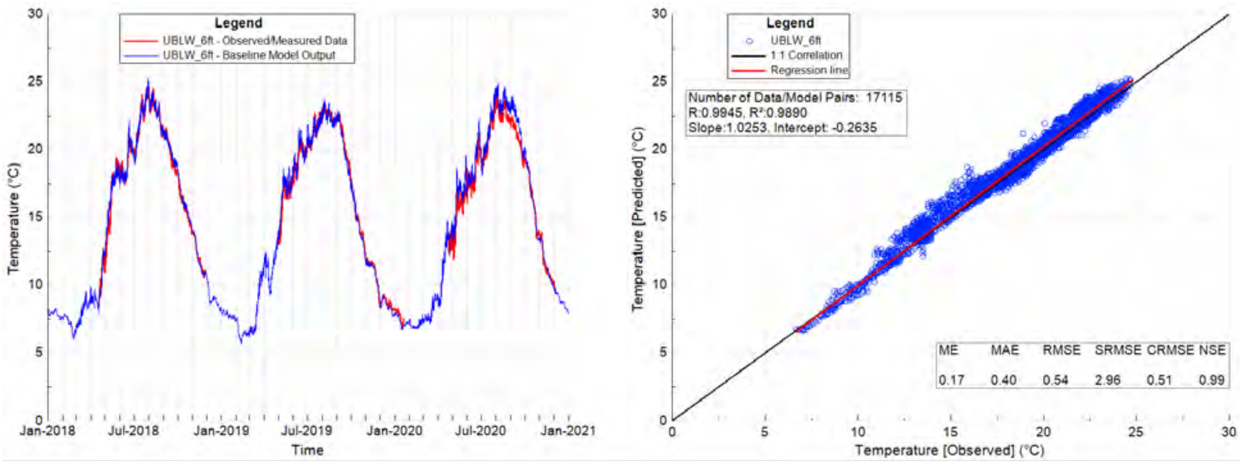

Figure A.1: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the University Bridge 6 ft depth station. Comparison statistics are provided in the scatterplot.

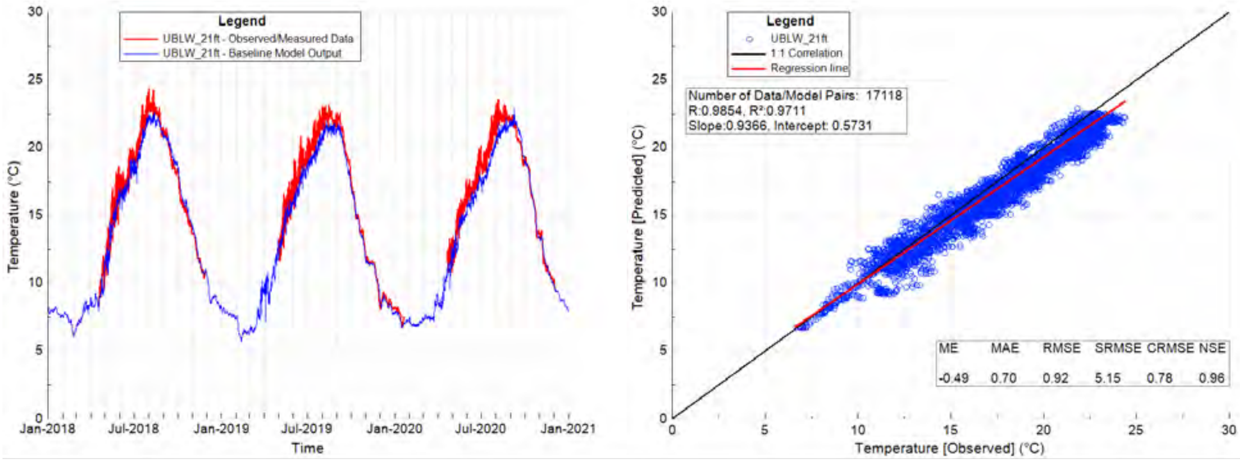

Figure A.2: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the University Bridge 21 ft depth station. Comparison statistics are provided in the scatterplot.

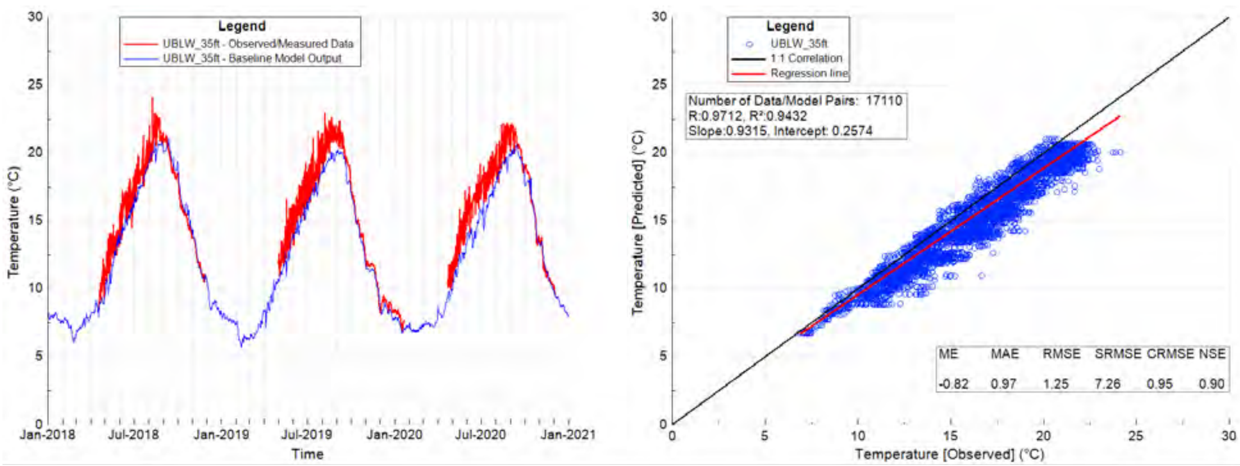

Figure A.3: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the University Bridge 35 ft depth station. Comparison statistics are provided in the scatterplot.

A.2 Gas Works Park

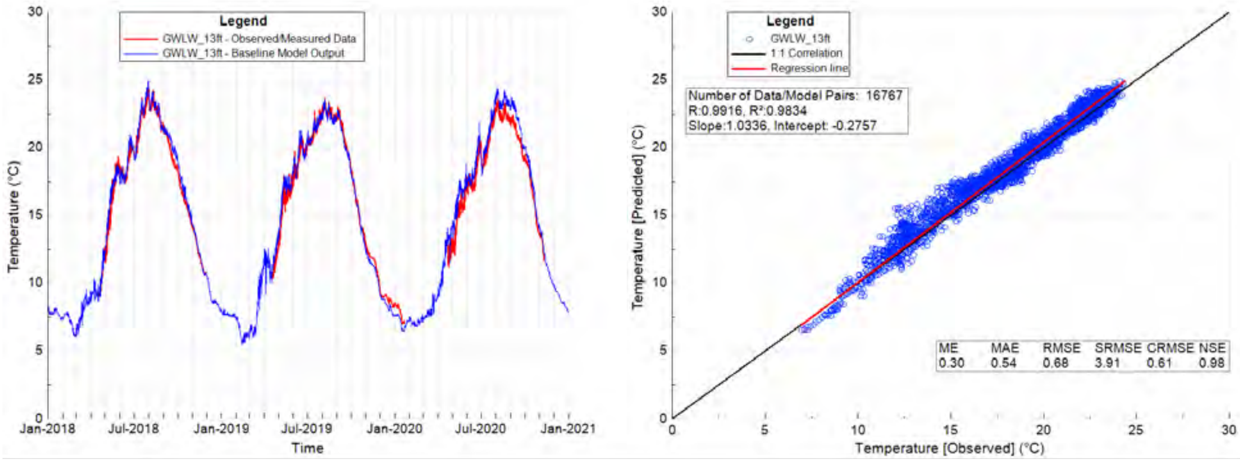

Figure A.4: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the Gas Works Park 13 ft depth station. Comparison statistics are provided in the scatterplot.

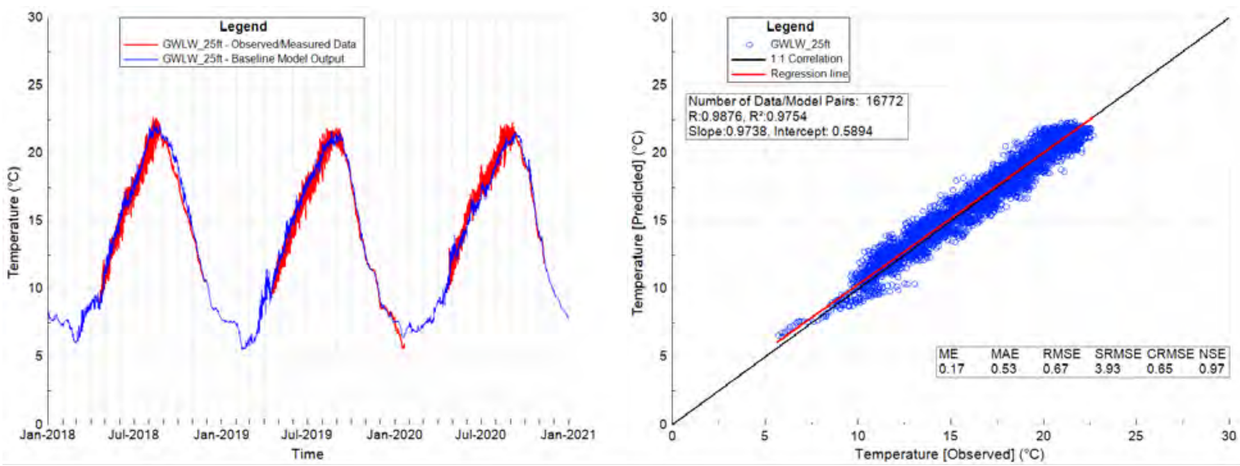

Figure A.5: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the Gas Works Park 25 ft depth station. Comparison statistics are provided in the scatterplot.

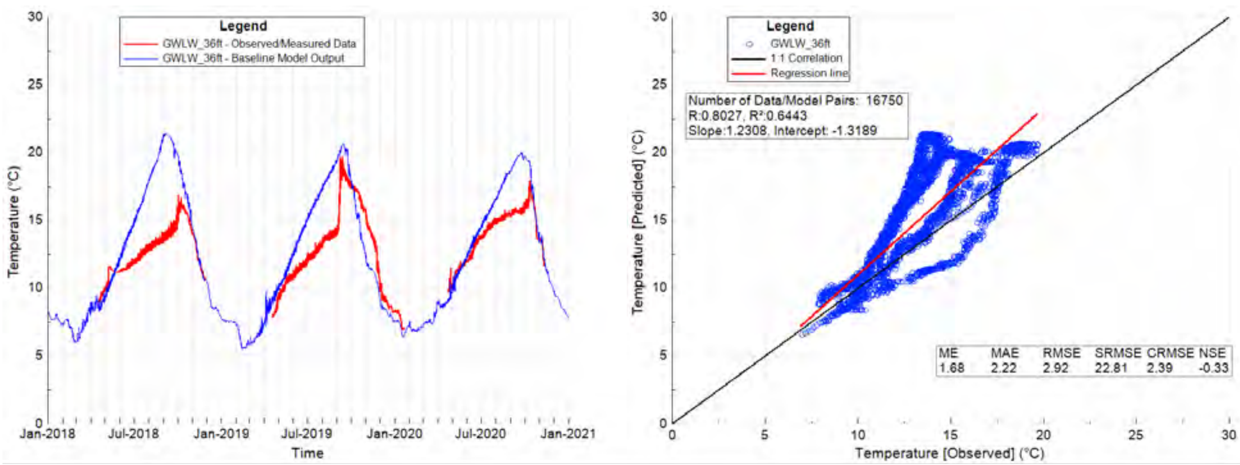

Figure A.6: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the Gas Works Park 36 ft depth station. Comparison statistics are provided in the scatterplot.

A.3 Fremont Bridge

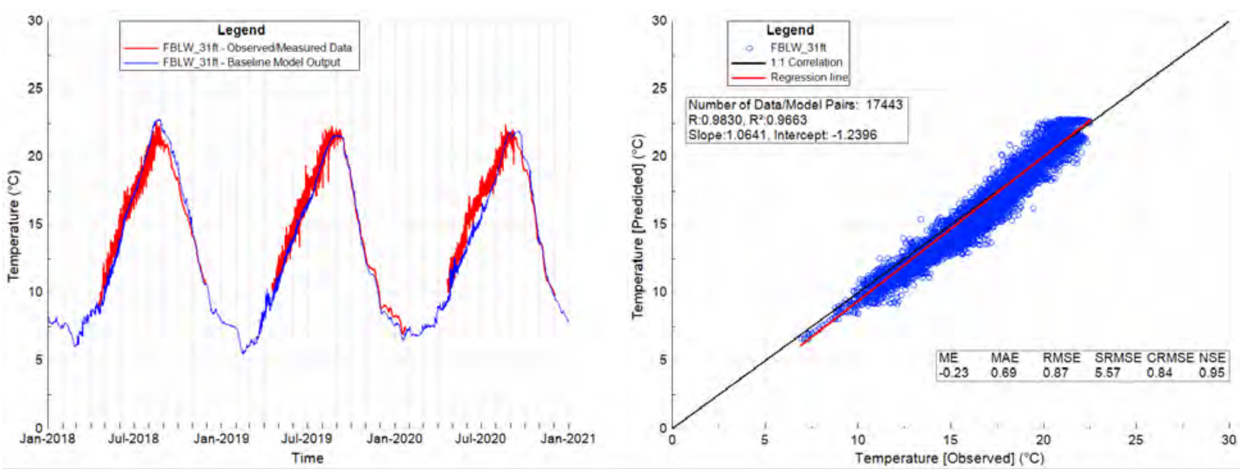

Figure A.7: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the Fremont Bridge 31 ft depth station. Comparison statistics are provided in the scatterplot.

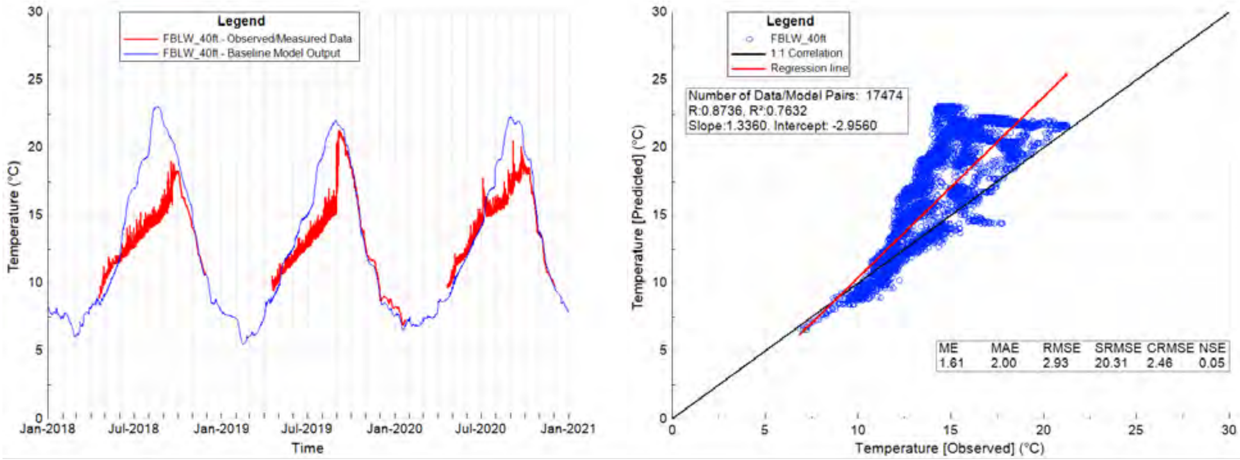

Figure A.8: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the Fremont Bridge 40 ft depth station. Comparison statistics are provided in the scatterplot.

A.4 Ballard Bridge

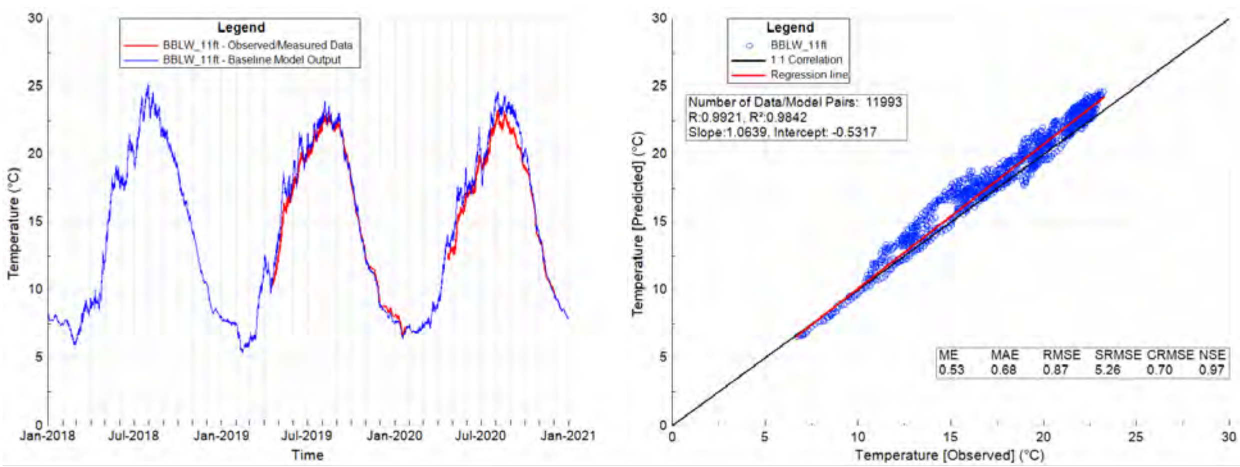

Figure A.9: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the Ballard Bridge 11 ft depth station. Comparison statistics are provided in the scatterplot.

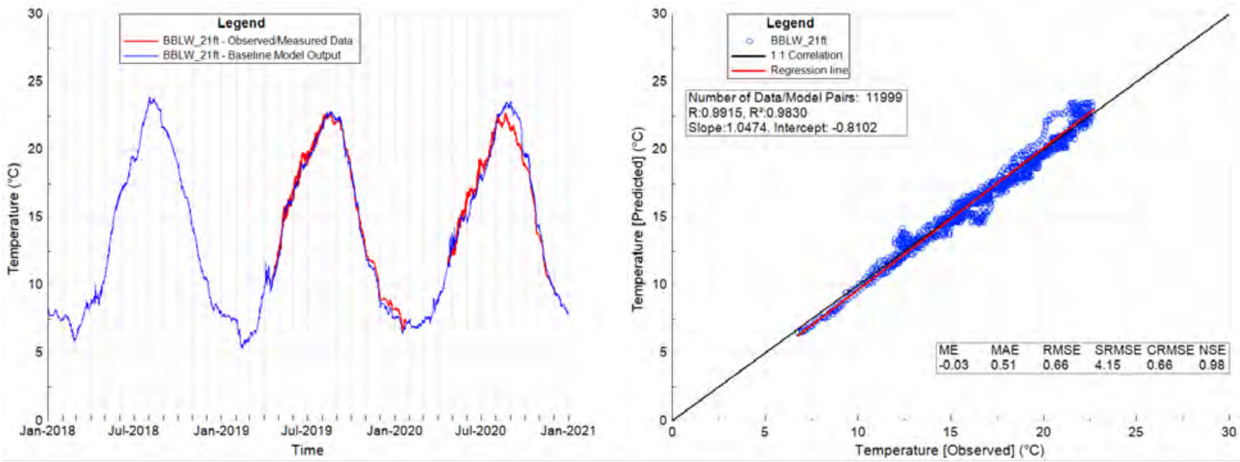

Figure A.10: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the Ballard Bridge 21 ft depth station. Comparison statistics are provided in the scatterplot.

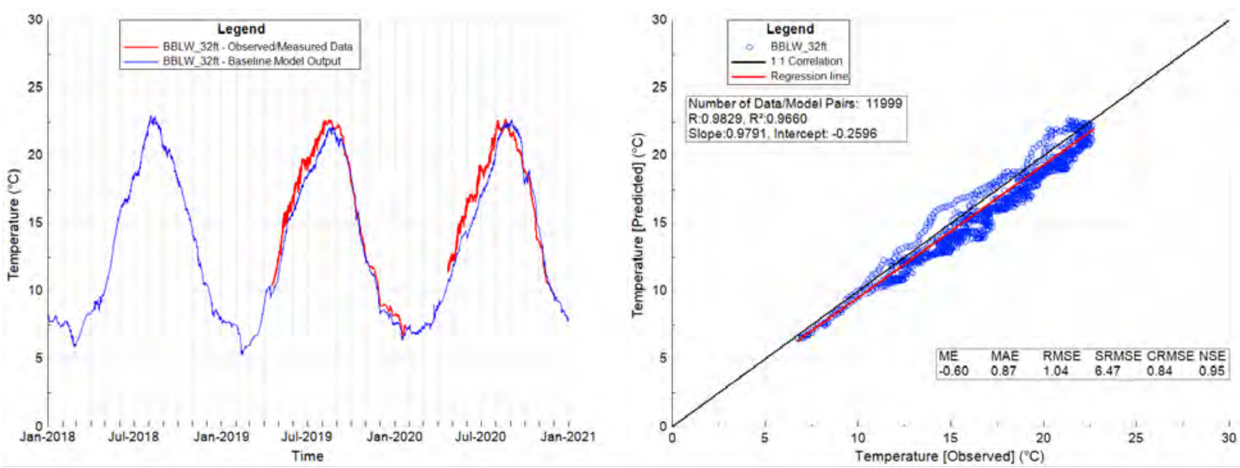

Figure A.11: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the Ballard Bridge 32 ft depth station. Comparison statistics are provided in the scatterplot.

A.5 Large Lock Station

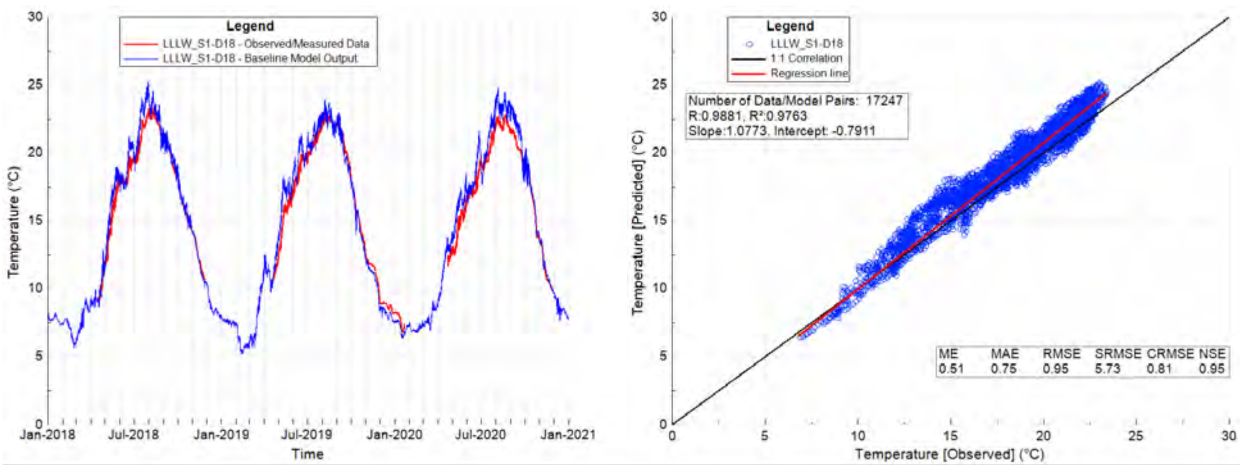

Figure A.12: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the Large Lock 18 ft depth station. Comparison statistics are provided in the scatterplot.

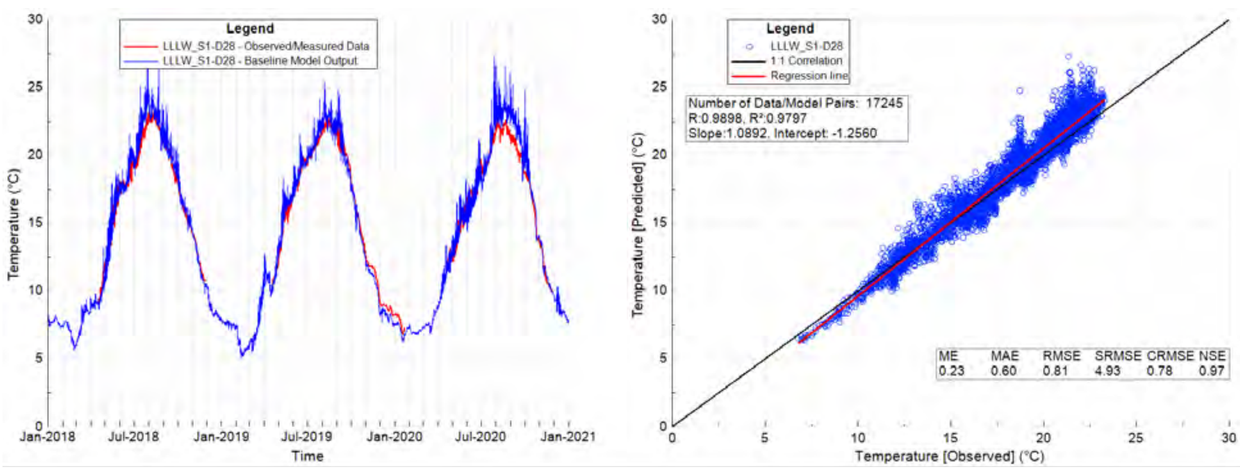

Figure A.13: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the Large Lock 28 ft depth station. Comparison statistics are provided in the scatterplot.

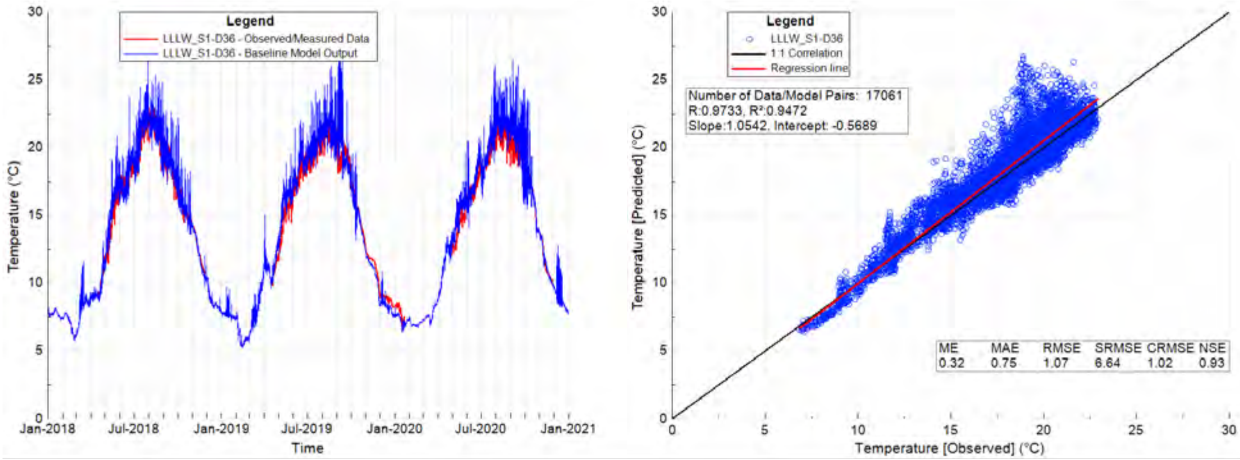

Figure A.14: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the Large Lock 36 ft depth station. Comparison statistics are provided in the scatterplot.

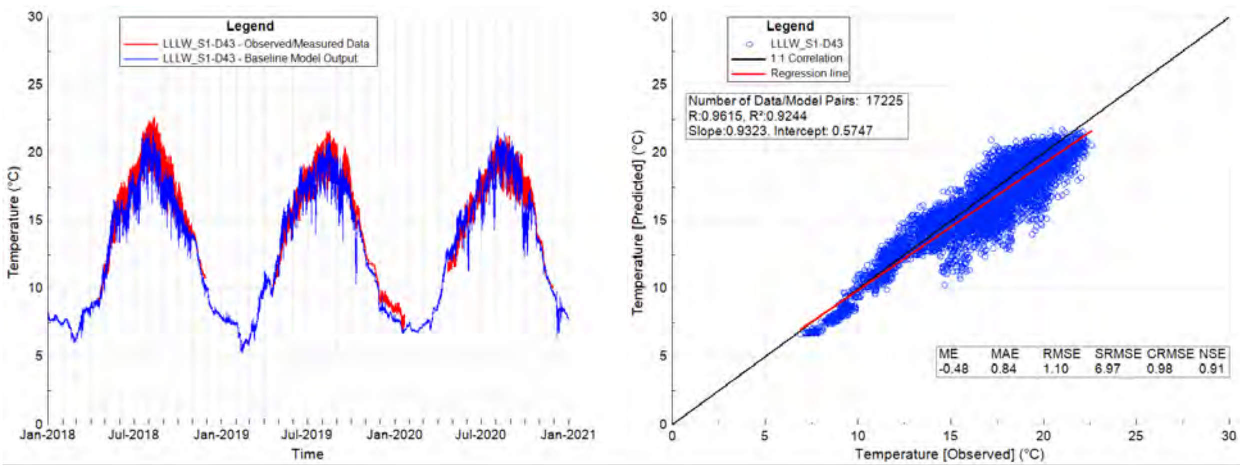

Figure A.15: (Left) Time series and (Right) Scatter plot comparison of the Baseline Model and Observed Temperature for the Large Lock 43 ft depth station. Comparison statistics are provided in the scatterplot.

B STATISTICAL OVERVIEW FOR ALL TIME SERIES TEMPERATURE STATIONS

Table B.1: Statistical overview of all time series temperatures stations.

Station ID	Depth (m)/Layer	Start Date	End Date	# Pairs	$\overline{O}$	$\overline{P}$	ME	MAE	RMSE	SRMSE	SS
LW_0804_1m	Depth 1.000	1/8/2018 0:00	12/14/2020 0:00	49	15.567	15.175	-0.392	0.829	1.198	7.489%	0.942
LW_0804_5m	Depth 5.000	3/12/2018 0:00	11/24/2020 0:00	4	13.025	13.289	0.264	0.564	0.664	4.201%	0.959
LW_0826_1m	Depth 1.000	2/12/2018 0:00	12/14/2020 0:00	53	14.572	14.432	-0.14	0.458	0.601	3.337%	0.986
LW_0826_5m	Depth 5.000	2/12/2018 0:00	12/14/2020 0:00	45	15.509	15.068	-0.441	0.618	0.77	4.301%	0.975
LW_0826_10m	Depth 10.000	3/12/2018 0:00	12/14/2020 0:00	23	14.387	13.062	-1.325	1.418	2.116	14.199%	0.827
LW_0826_15m	Depth 15.000	1/8/2018 0:00	11/24/2020 0:00	31	11.123	10.92	-0.203	0.926	1.338	13.519%	0.773
LW_0826_20m	Depth 20.000	3/12/2018 0:00	12/14/2020 0:00	24	9.704	9.073	-0.631	1.032	1.575	16.411%	0.500
LW_0826_30m	Depth 30.000	2/12/2018 0:00	12/14/2020 0:00	33	8.382	7.588	-0.794	0.866	0.971	25.564%	-0.018
LW_0826_40m	Depth 40.000	4/9/2018 0:00	12/14/2020 0:00	35	7.866	6.84	-1.026	1.026	1.081	41.568%	-1.155
LW_0852_1m	Depth 1.000	1/8/2018 0:00	12/14/2020 0:00	52	14.758	14.859	0.101	0.564	0.74	4.406%	0.967
LW_0852_5m	Depth 5.000	3/12/2018 0:00	12/14/2020 0:00	39	15.29	15.281	-0.009	0.407	0.572	3.741%	0.980
LW_0852_10m	Depth 10.000	1/8/2018 0:00	12/14/2020 0:00	39	13.51	12.469	-1.041	1.145	1.673	11.151%	0.853
LW_0852_15m	Depth 15.000	4/23/2018 0:00	12/14/2020 0:00	35	11.377	11.215	-0.162	0.704	0.922	10.026%	0.866
LW_0852_20m	Depth 20.000	1/8/2018 0:00	12/14/2020 0:00	43	9.553	9.496	-0.057	1.016	1.312	14.42%	0.520
LW_0852_30m	Depth 30.000	2/12/2018 0:00	12/14/2020 0:00	33	8.339	7.651	-0.688	0.766	0.888	26.122%	0.113
LW Buoy_1m	Depth 1.000	1/2/2018 8:03	12/29/2020 0:03	3517	15.487	15.191	-0.296	0.478	0.618	3.114%	0.983
LW Buoy_5m	Depth 5.000	1/2/2018 8:09	12/29/2020 0:09	2515	13.922	13.695	-0.228	0.504	0.657	3.598%	0.982
LW Buoy_10m	Depth 10.000	1/2/2018 8:17	12/28/2020 16:17	2976	13.636	12.77	-0.866	0.965	1.343	7.793%	0.894
LW Buoy_15m	Depth 15.000	1/2/2018 8:26	12/29/2020 0:25	3016	10.994	10.714	-0.28	0.899	1.159	9.405%	0.812
LW Buoy_20m	Depth 20.000	1/2/2018 8:34	12/29/2020 0:33	3009	9.302	9.094	-0.208	0.905	1.123	14.054%	0.412
LW Buoy_30m	Depth 30.000	1/2/2018 8:50	12/29/2020 0:49	3311	8.134	7.481	-0.653	0.683	0.806	18.242%	0.158
LW Buoy_40m	Depth 40.000	1/2/2018 9:06	12/29/2020 1:05	3504	7.775	6.894	-0.881	0.889	0.95	30.154%	-0.509
LW Buoy_50m	Depth 50.000	1/2/2018 9:22	12/29/2020 1:22	3587	7.582	6.672	-0.91	0.923	0.978	32.481%	-0.792
LW_0831_1m	Depth 1.000	1/8/2018 0:00	12/14/2020 0:00	56	13.905	14.805	0.9	0.946	1.37	7.327%	0.935
LW_0831_5m	Depth 5.000	2/12/2018 0:00	12/14/2020 0:00	38	13.789	14.525	0.735	1.384	1.861	10.225%	0.886
LW_0831_10m	Depth 10.000	1/8/2018 0:00	12/14/2020 0:00	42	14.107	13.969	-0.138	1.952	2.791	18.605%	0.666
LW_0831_15m	Depth 15.000	1/8/2018 0:00	12/14/2020 0:00	42	10.548	10.8	0.253	1.432	1.902	16.542%	0.574
LW_0831_20m	Depth 20.000	1/8/2018 0:00	11/9/2020 0:00	30	9.073	9.252	0.179	1.132	1.405	19.249%	0.488
LU_0540_1m	Depth 1.000	3/26/2018 0:00	12/14/2020 0:00	50	15.45	15.65	0.2	0.539	0.648	3.81%	0.966
LU_0540_5m	Depth 5.000	3/12/2018 0:00	12/14/2020 0:00	38	15.261	15.158	-0.102	0.505	0.631	3.802%	0.970
UBLW_6ft	Depth 1.830	4/17/2018 9:00	12/3/2020 9:00	17115	17.215	17.388	0.173	0.401	0.537	2.964%	0.976
UBLW_21ft	Depth 6.400	4/17/2018 9:00	12/3/2020 9:00	17118	16.689	16.204	-0.485	0.699	0.915	5.145%	0.949
UBLW_35ft	Depth 10.100	4/17/2018 9:00	12/3/2020 9:00	17110	15.75	14.929	-0.822	0.969	1.254	7.259%	0.914
GWLW_3ft	Depth 0.910	4/17/2018 9:00	11/10/2020 6:00	16771	17.486	17.686	0.2	0.473	0.602	3.322%	0.969
GWLW_13ft	Depth 3.960	4/17/2018 9:00	11/10/2020 6:00	16767	17.268	17.572	0.304	0.535	0.682	3.909%	0.964
GWLW_25ft	Depth 7.620	4/17/2018 9:00	11/10/2020 6:00	16772	15.888	16.061	0.173	0.528	0.67	3.927%	0.976
GWLW_36ft	Depth 10.970	4/17/2018 9:00	11/10/2020 6:00	16750	12.976	14.652	1.675	2.221	2.915	22.814%	0.044
LU_A522_1m	Depth 1.000	2/12/2018 0:00	12/14/2020 0:00	53	14.76	15.099	0.339	0.532	0.707	4.42%	0.962
LU_A522_5m	Depth 5.000	3/12/2018 0:00	12/14/2020 0:00	46	15.207	15.457	0.25	0.515	0.676	4.17%	0.972
LU_A522_10m	Depth 10.000	2/12/2018 0:00	12/14/2020 0:00	40	13.81	13.668	-0.142	0.793	1.107	8.262%	0.927
FBLW_18ft	Depth 5.490	4/17/2018 9:00	12/3/2020 10:00	17437	16.818	16.943	0.126	0.532	0.673	3.935%	0.974
FBLW_31ft	Depth 9.450	4/17/2018 9:00	12/3/2020 10:00	17443	15.753	15.523	-0.23	0.689	0.872	5.567%	0.934
FBLW_40ft	Depth 12.190	4/17/2018 9:00	12/3/2020 10:00	17474	13.577	15.182	1.605	1.996	2.934	20.313%	0.246
BBLW_11ft	Depth 3.350	4/18/2019 9:00	12/3/2020 11:00	11993	16.588	17.117	0.529	0.682	0.873	5.257%	0.942
BBLW_21ft	Depth 6.400	4/18/2019 9:00	12/3/2020 11:00	11999	16.375	16.341	-0.034	0.511	0.664	4.148%	0.961
BBLW_32ft	Layer 61	4/18/2019 9:00	12/3/2020 11:00	11999	16.375	15.773	-0.602	0.869	1.035	6.469%	0.953
LU_0512_1m	Depth 1.000	1/8/2018 0:00	12/14/2020 0:00	62	14.626	14.792	0.167	0.491	0.656	3.834%	0.955
LU_0512_5m	Depth 5.000	2/12/2018 0:00	12/14/2020 0:00	44	14.923	15.143	0.22	0.472	0.629	3.768%	0.951
LLLW_S1-D18	Depth 4.393	4/17/2018 11:00	11/29/2020 1:00	17247	16.78	17.286	0.506	0.746	0.952	5.733%	0.928
LLLW_S1-D28	Depth 7.433	4/17/2018 11:00	11/29/2020 1:00	17245	16.692	16.924	0.232	0.603	0.813	4.928%	0.931
LLLW_S1-D36	Depth 9.873	4/17/2018 11:00	11/29/2020 1:00	17061	16.334	16.65	0.316	0.747	1.069	6.636%	0.92
LLLW_S1-D43	Depth 12.013	4/17/2018 11:00	11/29/2020 1:00	17225	15.643	15.159	-0.484	0.84	1.096	6.973%	0.924

C SCENARIO RESULTS, FIGURES AND TABLES

C.1 Temperature Results for Selected Stations

C.1.1 University Bridge Temperature Results

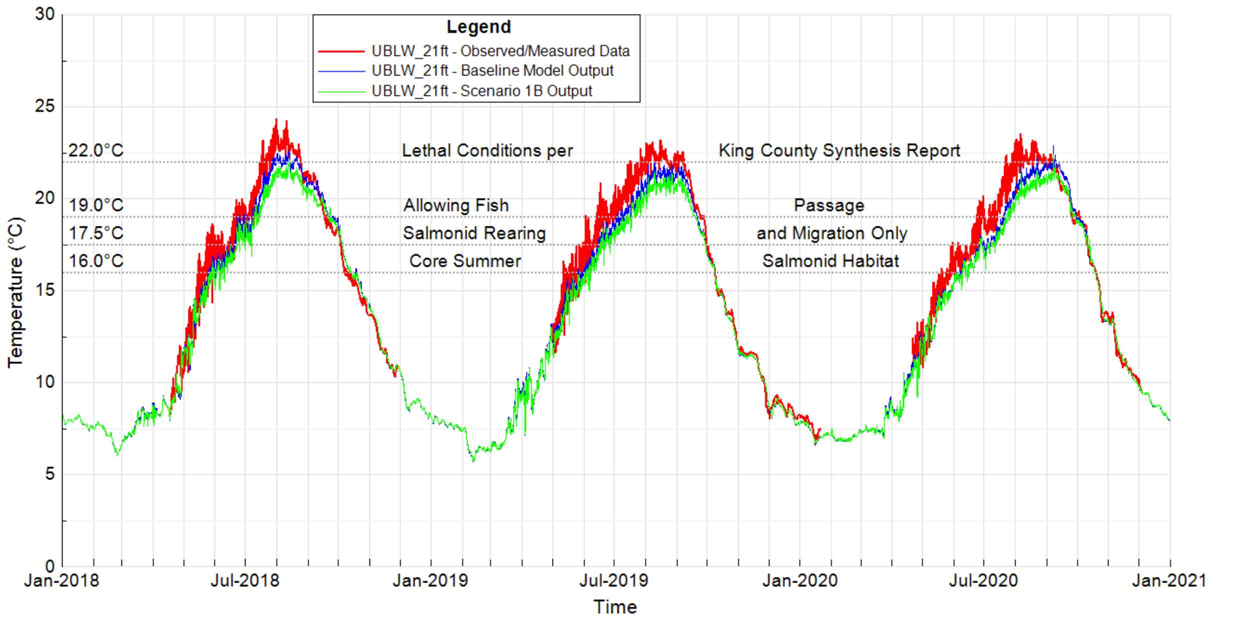

Figure C.1: Water temperature output comparison over time, 2018 - 2021: University Bridge-21ft depth Scenario 1B.

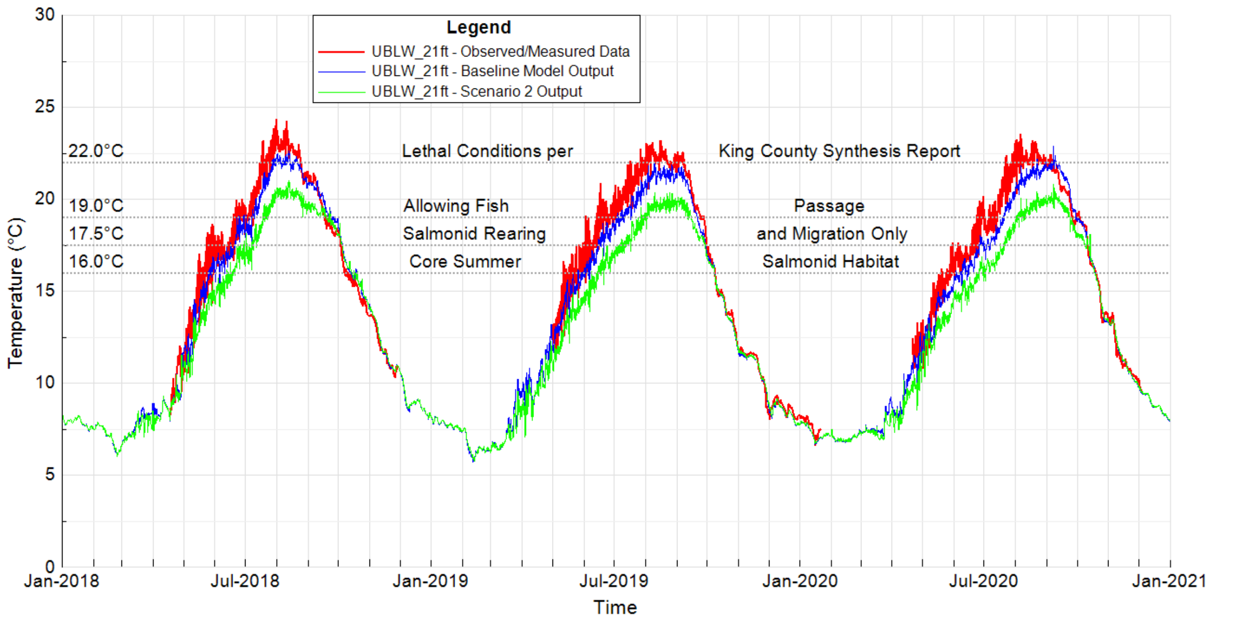

Figure C.2: Water temperature output comparison over time, 2018 - 2021: University Bridge-21ft depth Scenario 2.

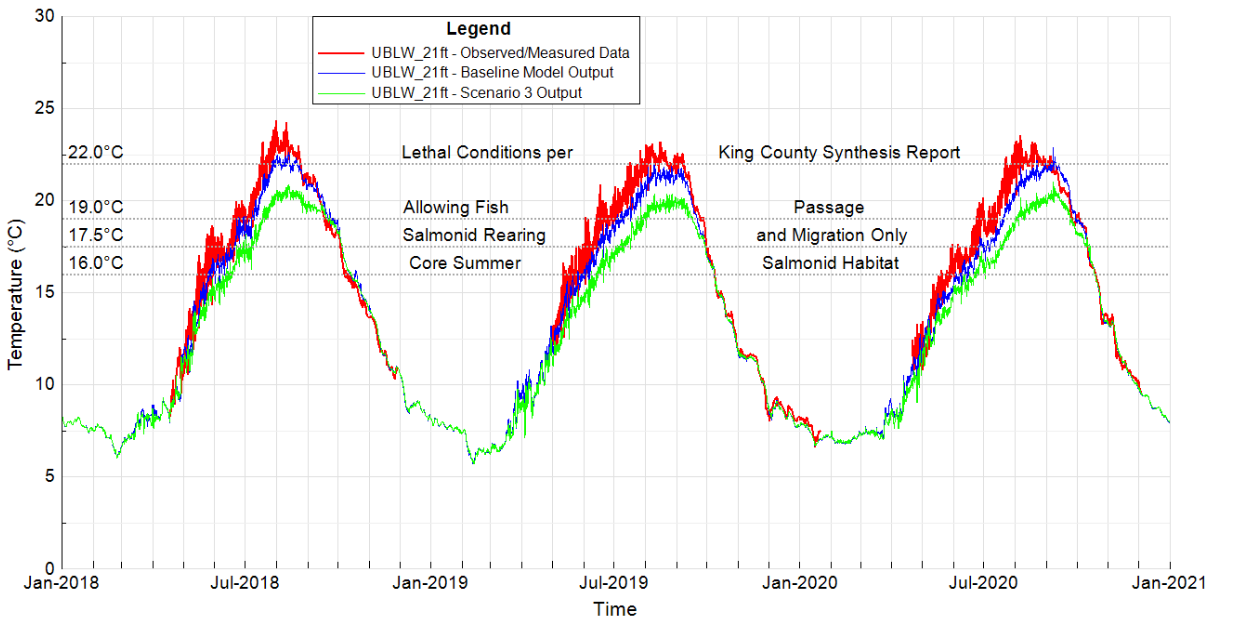

Figure C.3: Water temperature output comparison over time, 2018 - 2021: University Bridge-21ft depth Scenario 3.

C.1.2 Gas Works Park Temperature Results

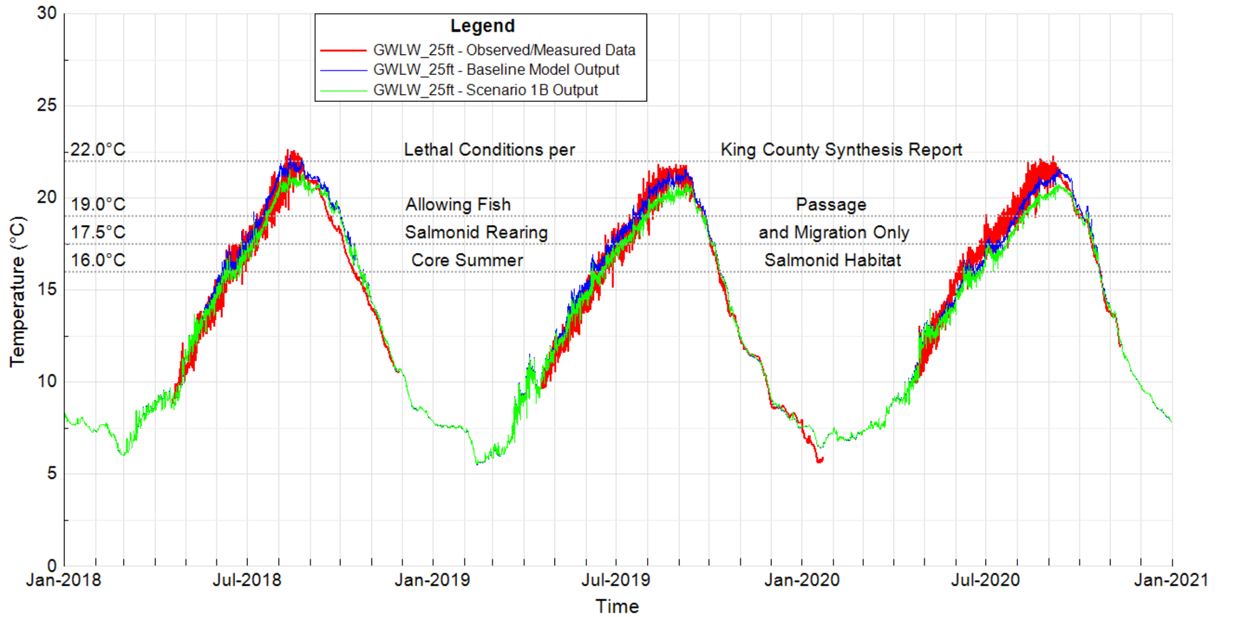

Figure C.4: Water temperature output comparison over time, 2018 - 2021: Gas Works Park 25ft depth Scenario 1B.

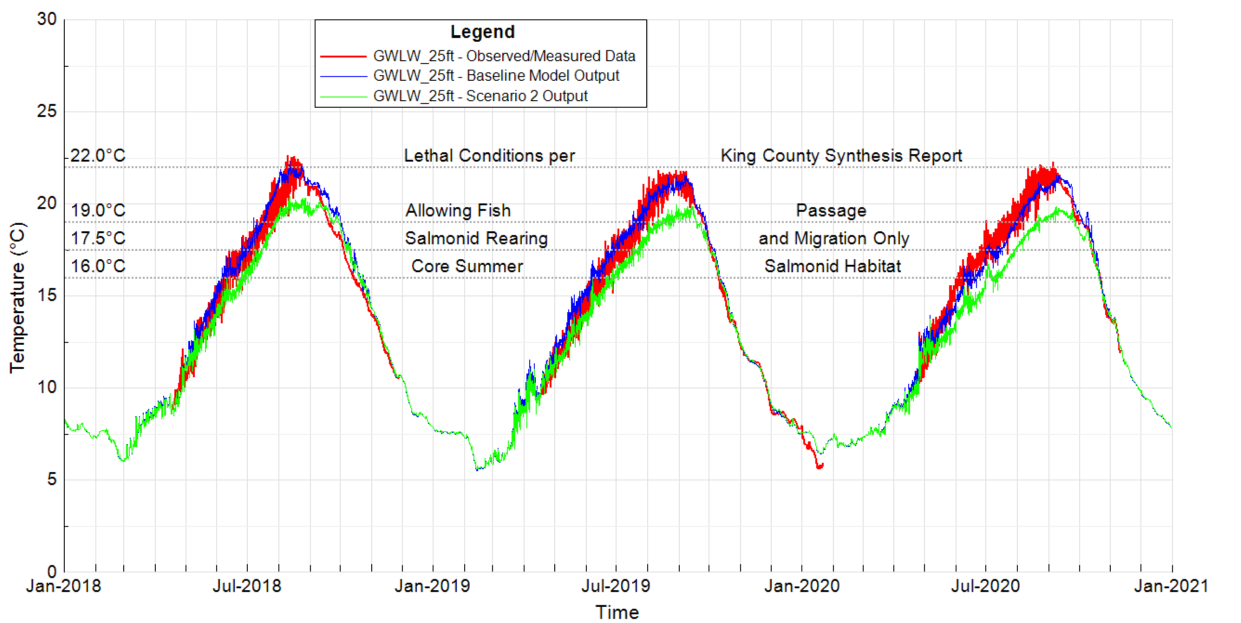

Figure C.5: Water temperature output comparison over time, 2018 - 2021: Gas Works Park 25ft depth Scenario 2.

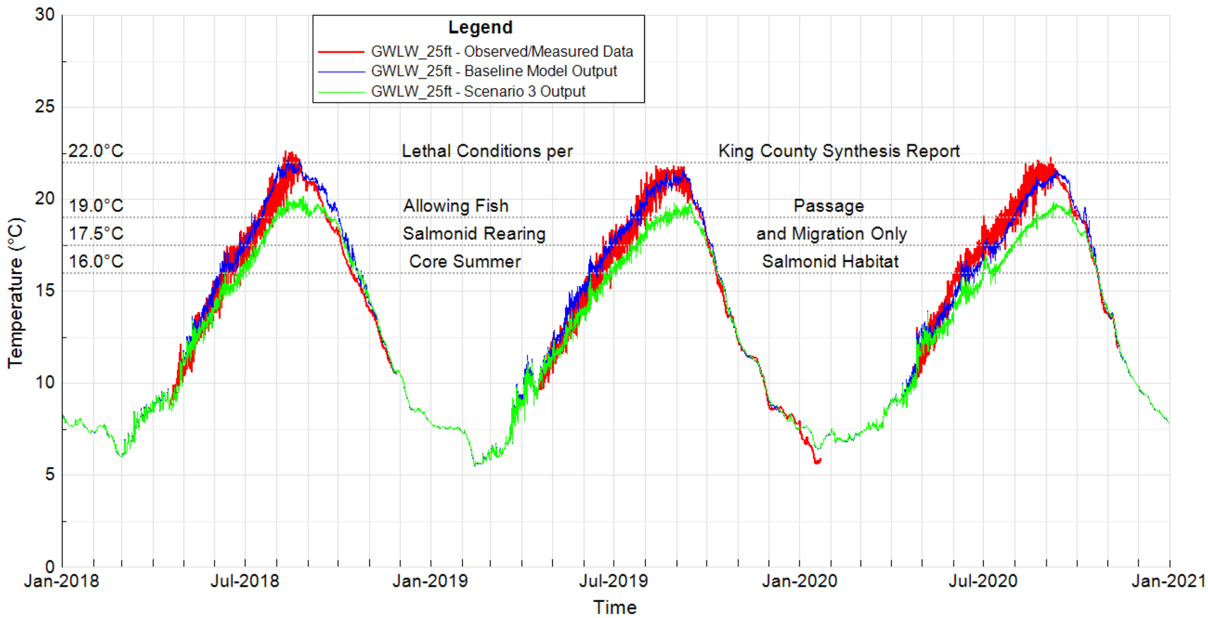

Figure C.6: Water temperature output comparison over time, 2018 - 2021: Gas Works Park 25ft depth Scenario 3.

C.1.3 Fremont Bridge Temperature Results

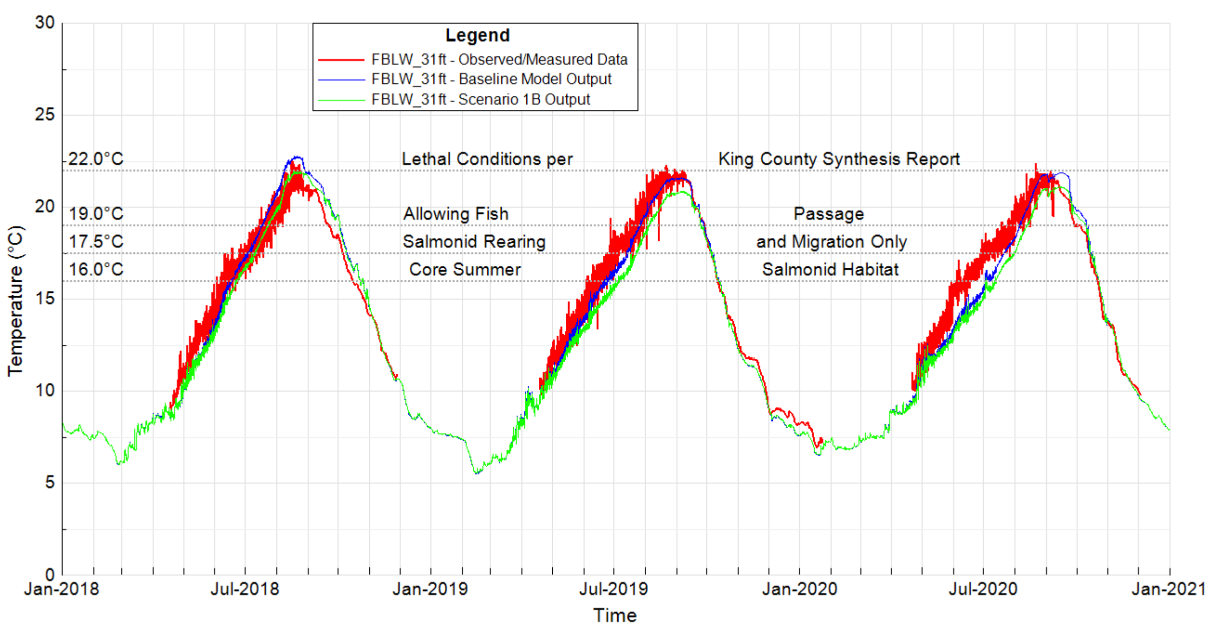

Figure C.7: Water temperature output comparison over time, 2018 - 2021: Fremont Bridge 31ft depth Scenario 1B.

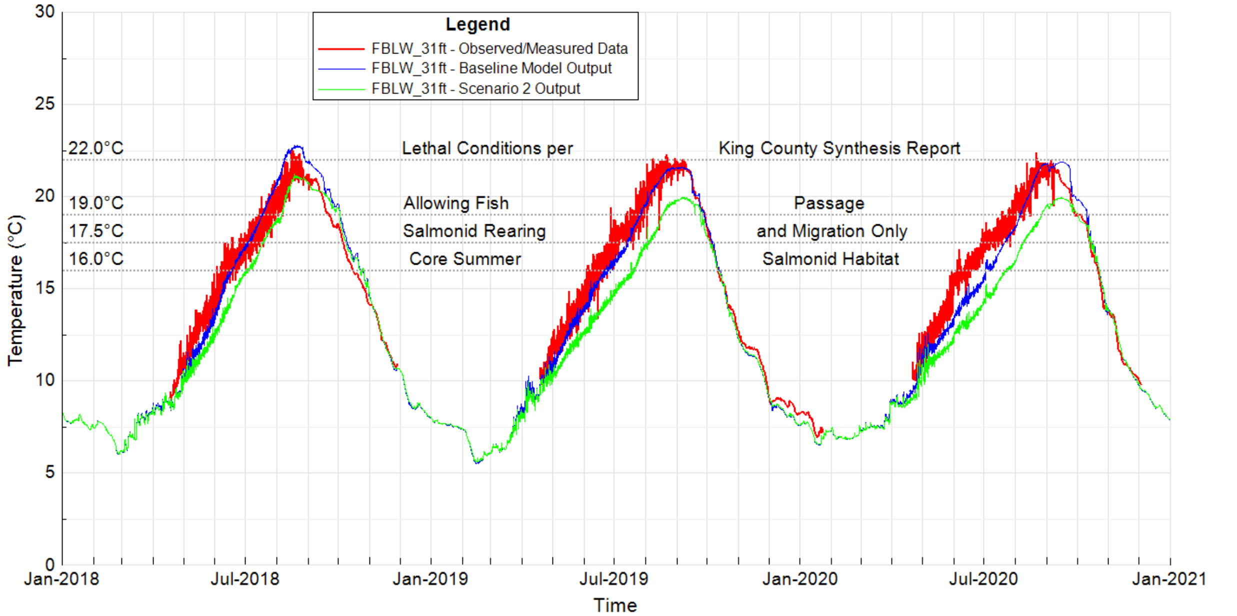

Figure C.8: Water temperature output comparison over time, 2018 - 2021: Fremont Bridge 31ft depth Scenario 2.

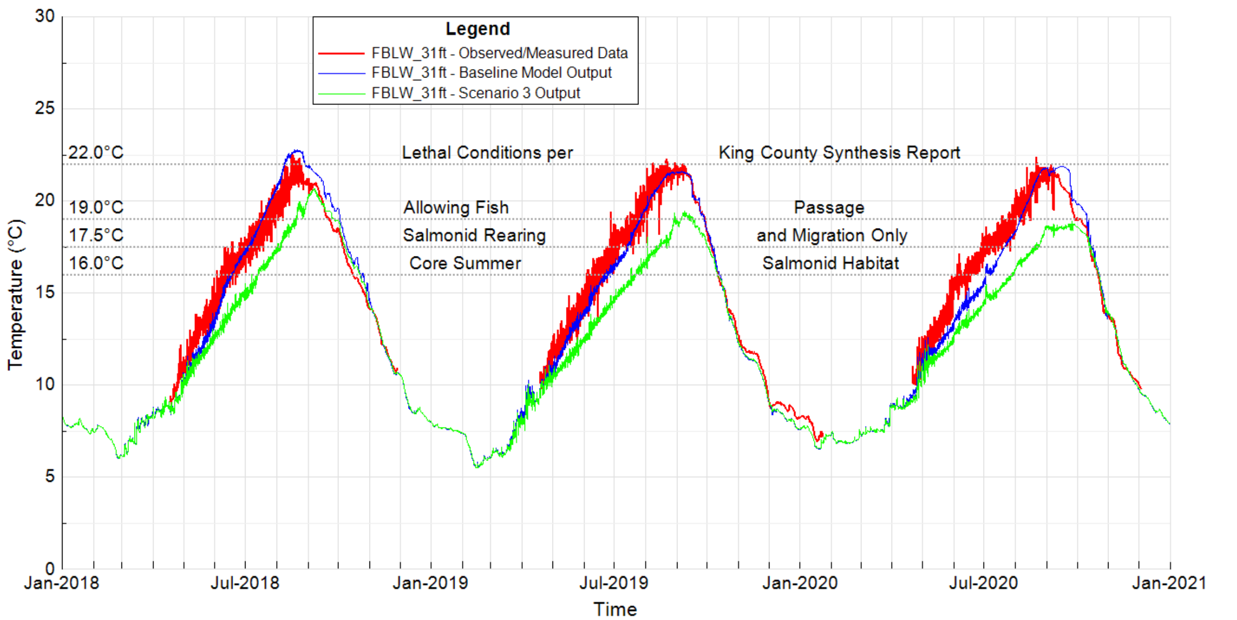

Figure C.9: Water temperature output comparison over time, 2018 - 2021: Fremont Bridge 31ft depth Scenario 3.

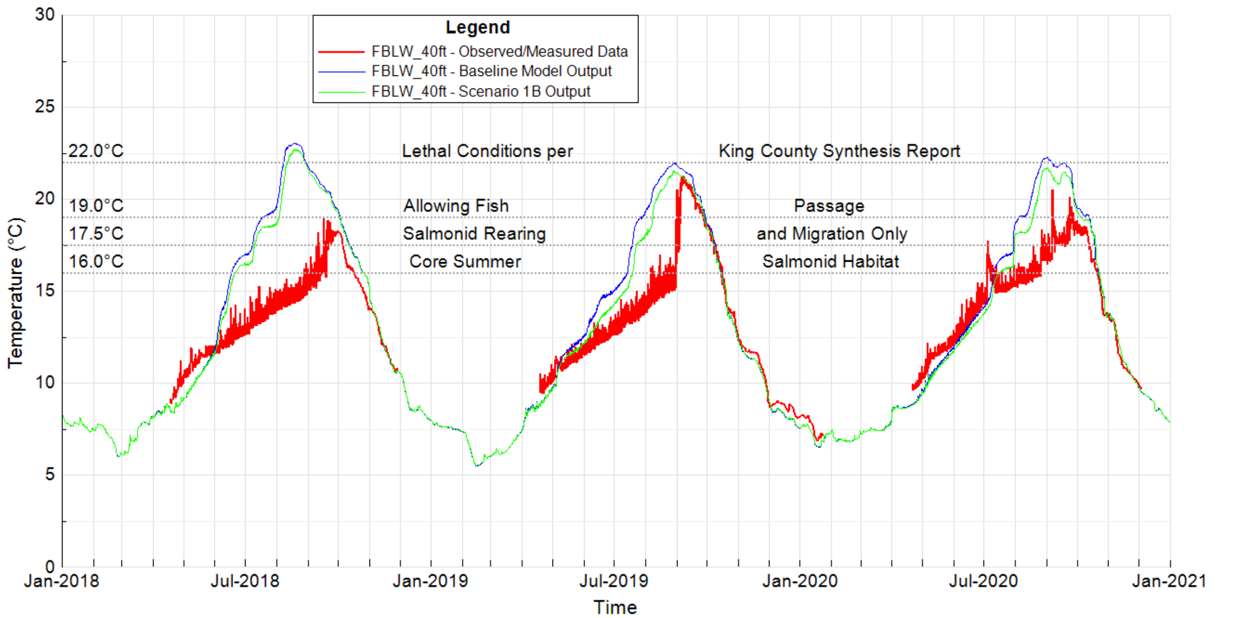

Figure C.10: Water temperature output comparison over time, 2018 - 2021: Fremont Bridge 40ft depth Scenario 1B.

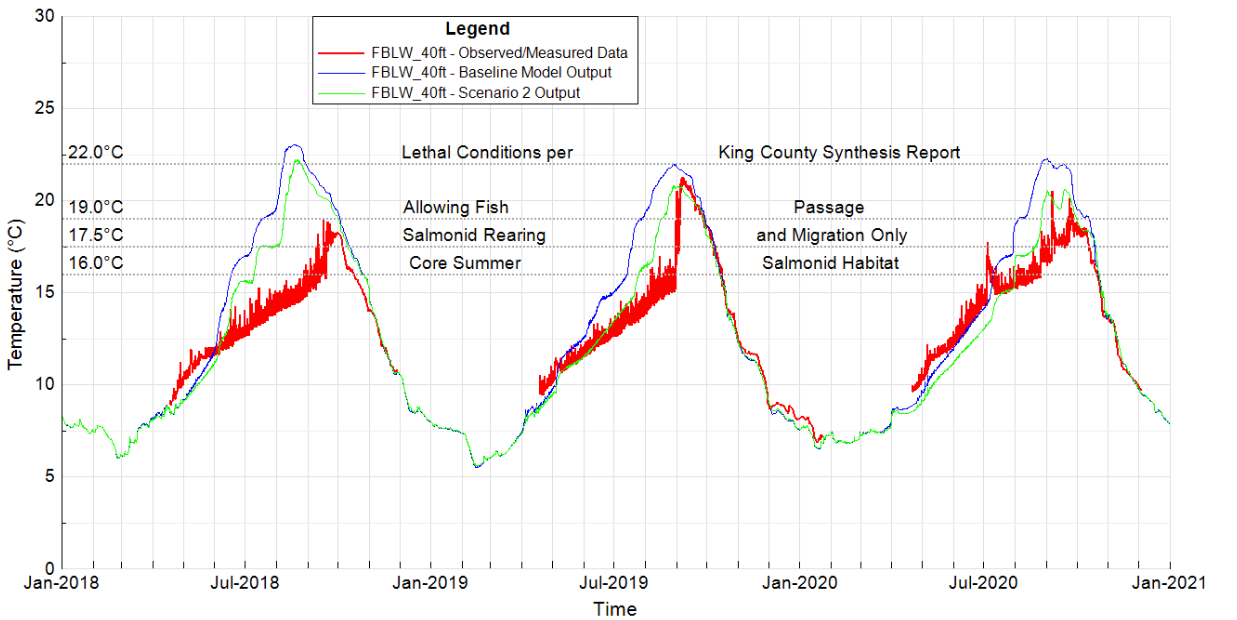

Figure C.11: Water temperature output comparison over time, 2018 - 2021: Fremont Bridge 40ft depth Scenario 2.

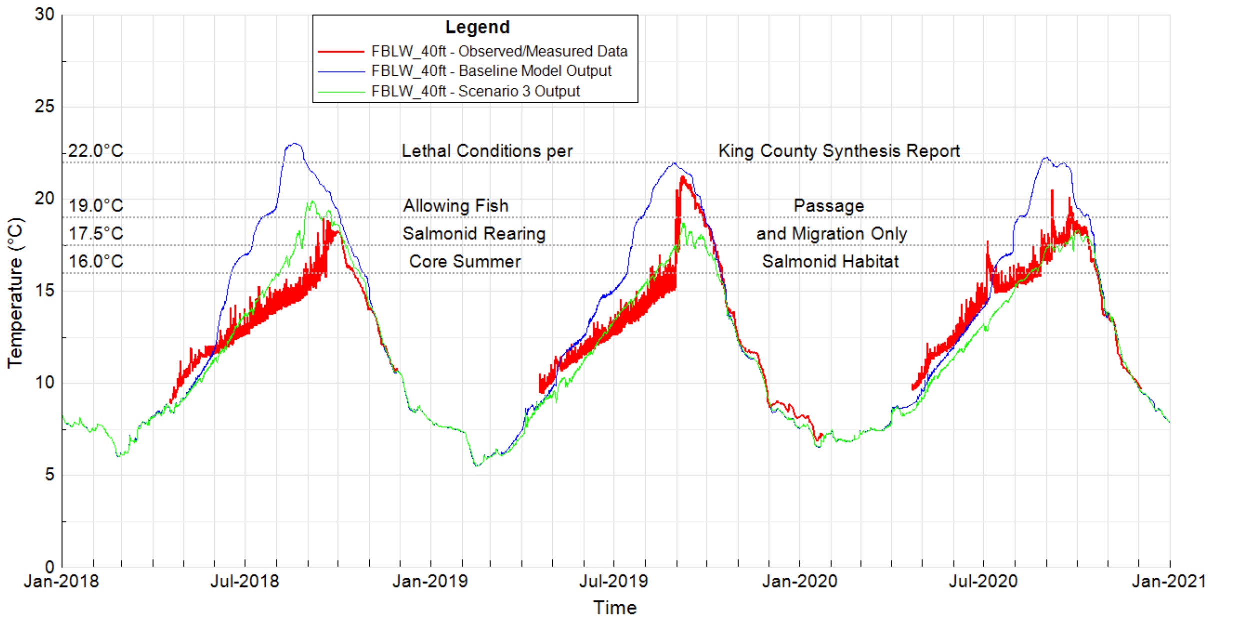

Figure C.12: Water temperature output comparison over time, 2018 - 2021: Fremont Bridge 40ft depth Scenario 3.

C.1.4 Ballard Bridge Temperature Results

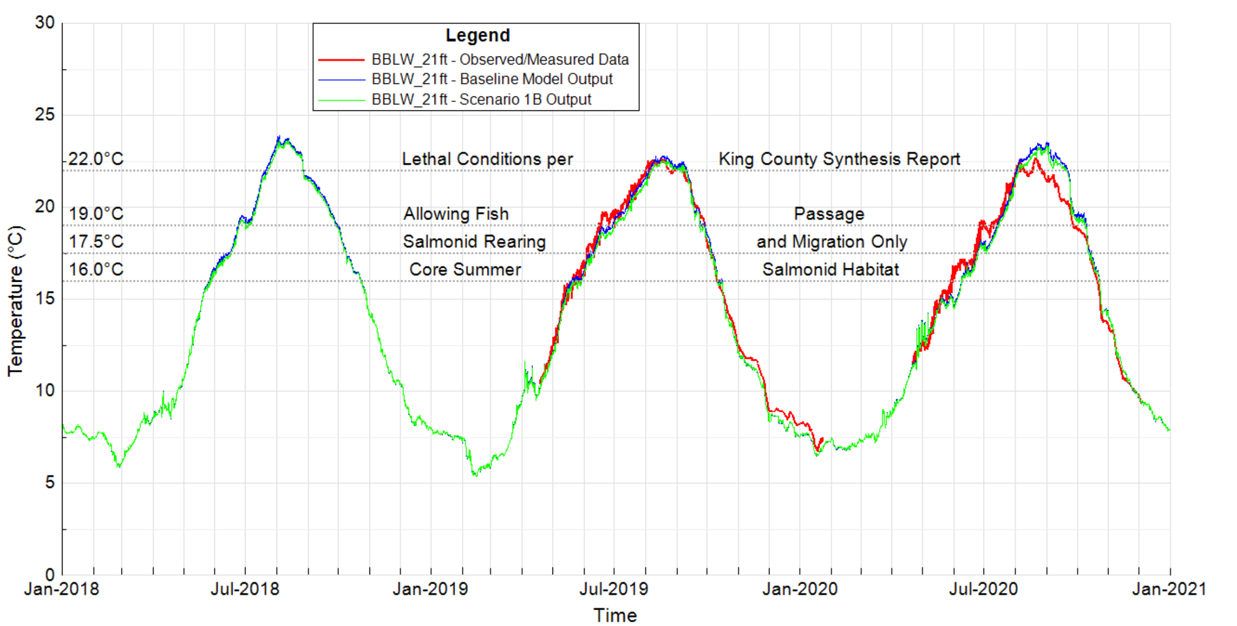

Figure C.13: Water temperature output comparison over time, 2018 - 2021: Ballard Bridge 21ft depth Scenario 1B.

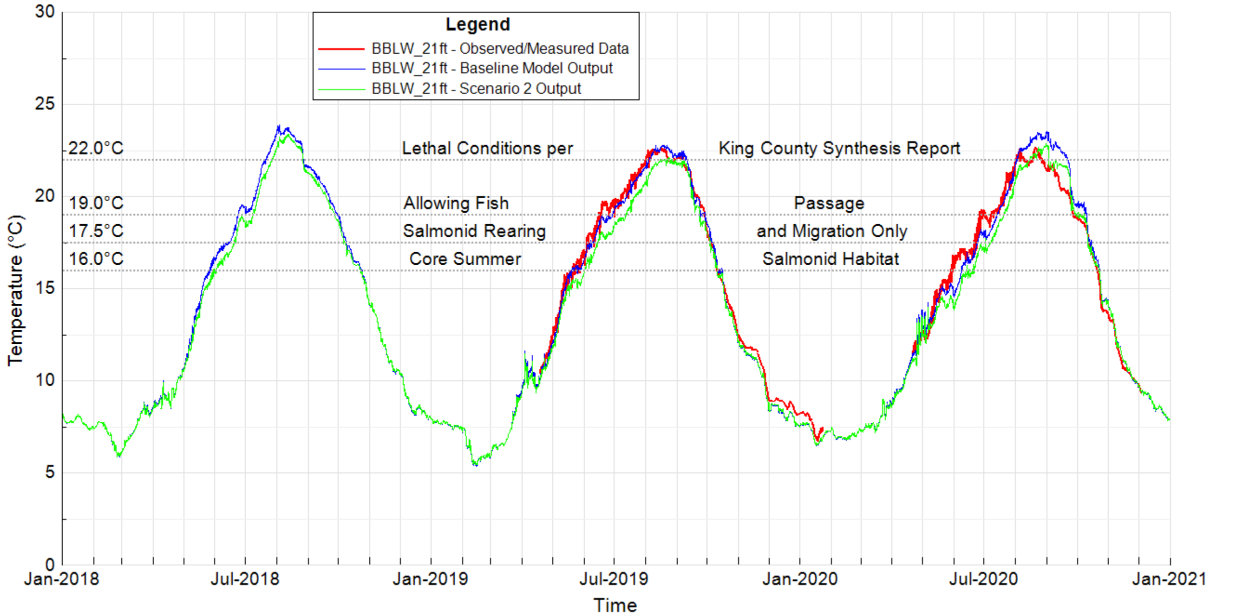

Figure C.14: Water temperature output comparison over time, 2018 - 2021: Ballard Bridge 21ft depth Scenario 2.

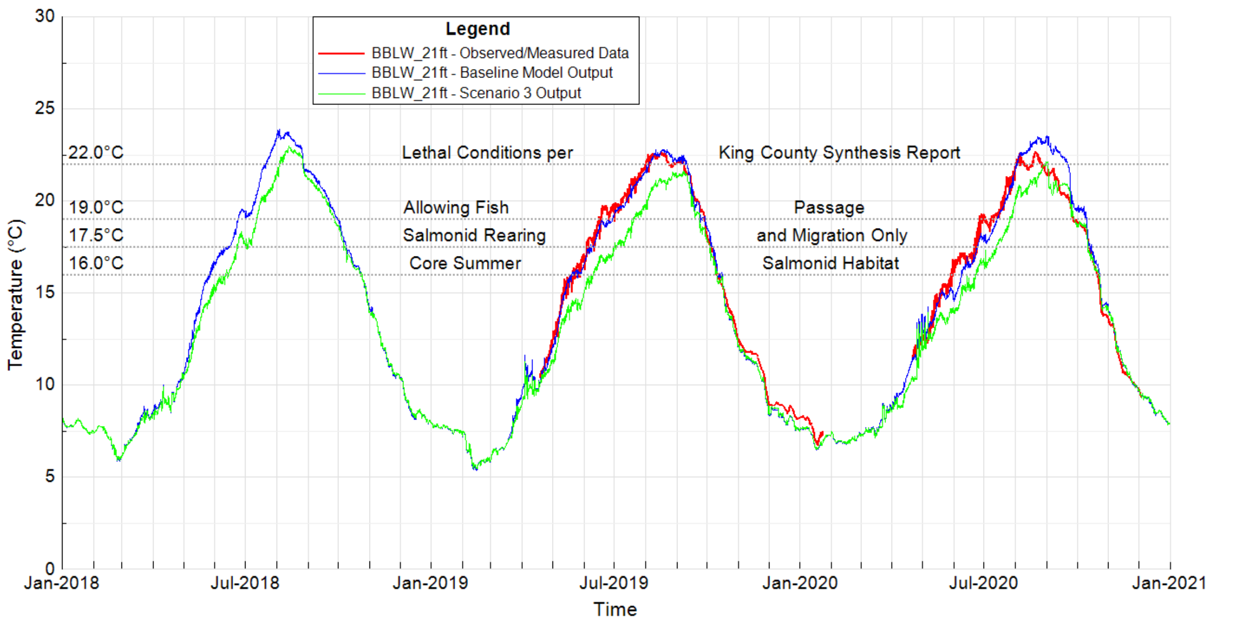

Figure C.15: Water temperature output comparison over time, 2018 - 2021: Ballard Bridge 21ft depth Scenario 3.

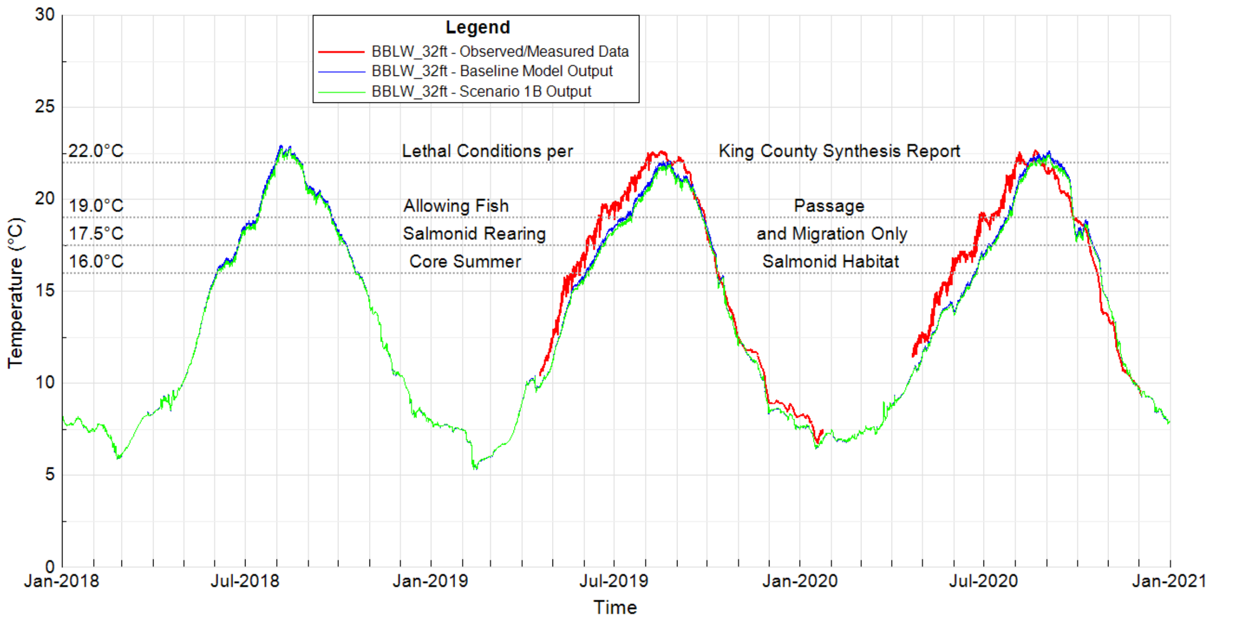

Figure C.16: Water temperature output comparison over time, 2018 - 2021: Ballard Bridge 32ft depth Scenario 1B.

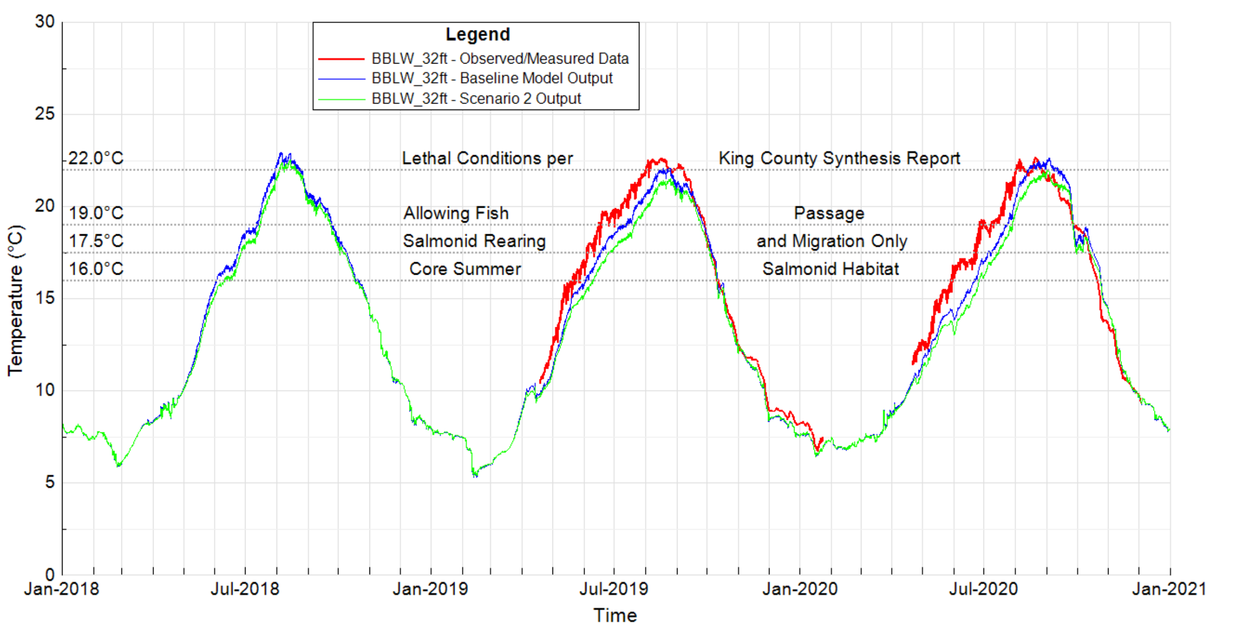

Figure C.17: Water temperature output comparison over time, 2018 - 2021: Ballard Bridge 32ft depth Scenario 2.

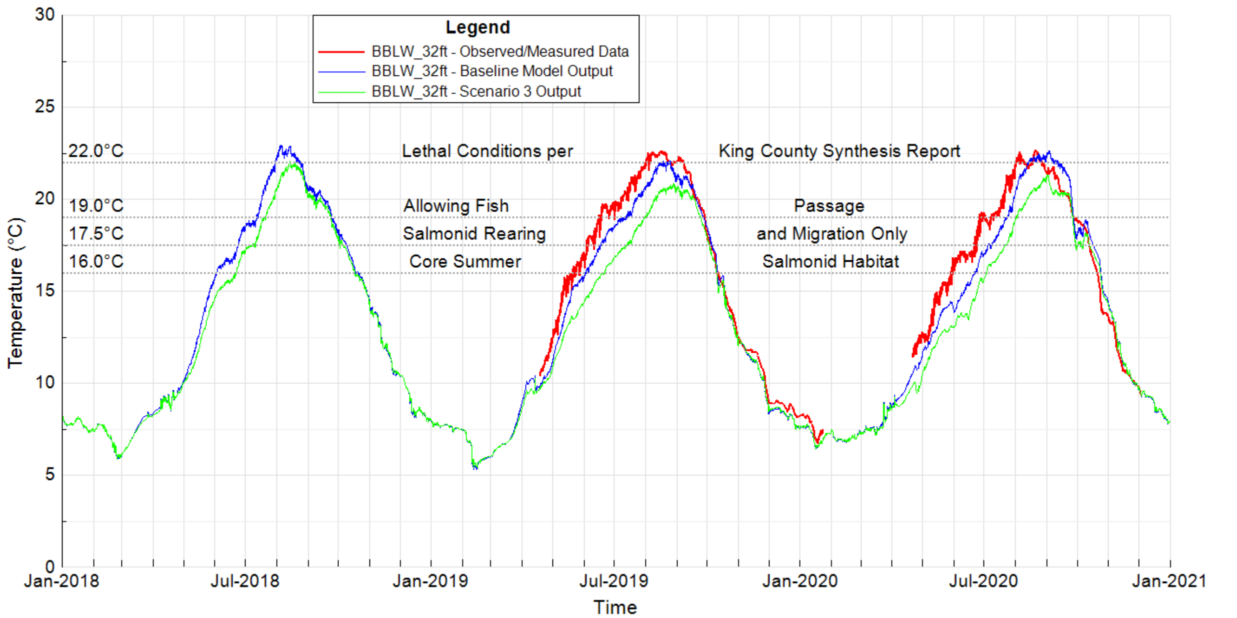

Figure C.18: Water temperature output comparison over time, 2018 - 2021: Ballard Bridge 32ft depth Scenario 3.

C.2 Temperature Threshold Exceedances for LWSC Time Series Stations

The statistics calculated in Tables C.1 to C.18 presents the statistical analysis of the percentage of days with temperature exceeding the predefined limits (16°C, 17.5°C, 19°C, and 22°C) at the specified monitoring stations, comparing both the baseline and scenario models. These statistics demonstrate the extent of reduction in the number of days where temperature surpassed the designated thresholds critical for salmon. They provide quantitative insights into the performance and effectiveness of scenarios 1B, 2, and 3 in mitigating temperature-related concerns for years 2018, 2019, and 2020 for each of the stations.

Table C.1: Percent of days during critical periods (May through September) with temperature above the limit (2018) University Bridge-21ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	17%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	97%	37%	2%	0%	85%	26%	0%	0%	40%	2%	0%	0%	47%	3%	0%	0%
July	100%	100%	79%	8%	100%	99%	64%	0%	100%	78%	40%	0%	100%	81%	43%	0%
August	100%	100%	100%	41%	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	100%	0%
September	100%	100%	75%	0%	100%	100%	70%	0%	100%	100%	64%	0%	100%	100%	69%	0%
October	44%	13%	0%	0%	43%	13%	0%	0%	45%	13%	0%	0%	42%	13%	0%	0%

Table C.2: Percent of days during critical periods (May through September) with temperature above the limit (2019) University Bridge-21ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	93%	50%	0%	0%	84%	35%	0%	0%	50%	0%	0%	0%	54%	0%	0%	0%
July	100%	100%	78%	0%	100%	100%	49%	0%	100%	70%	7%	0%	100%	76%	10%	0%
August	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	97%	0%	100%	100%	98%	0%
September	100%	96%	67%	0%	100%	94%	61%	0%	100%	93%	47%	0%	100%	94%	53%	0%
October	24%	0%	0%	0%	23%	0%	0%	0%	23%	0%	0%	0%	24%	0%	0%	0%

Table C.3: Percent of days during critical periods (May through September) with temperature above the limit (2020) University Bridge-21ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	69%	15%	0%	0%	65%	7%	0%	0%	16%	0%	0%	0%	29%	0%	0%	0%
July	100%	87%	38%	0%	100%	74%	26%	0%	97%	37%	0%	0%	99%	45%	0%	0%
August	100%	100%	100%	1%	100%	100%	100%	0%	100%	100%	89%	0%	100%	100%	93%	0%
September	100%	100%	96%	7%	100%	100%	94%	1%	100%	100%	76%	0%	100%	100%	76%	0%
October	58%	36%	0%	0%	58%	36%	0%	0%	57%	33%	0%	0%	58%	37%	0%	0%

Table C.4: Percent of days during critical periods (May through September) with temperature above the limit (2018) Gas Works Park 25ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	81%	5%	0%	0%	50%	1%	0%	0%	13%	0%	0%	0%	14%	0%	0%	0%
July	100%	98%	49%	0%	100%	82%	38%	0%	98%	52%	10%	0%	98%	50%	5%	0%
August	100%	100%	100%	4%	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	99%	0%
September	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	88%	0%	100%	100%	69%	0%
October	65%	31%	1%	0%	63%	26%	0%	0%	62%	26%	0%	0%	64%	22%	0%	0%

Table C.5: Percent of days during critical periods (May through September) with temperature above the limit (2019) Gas Works Park 25ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
July	100%	99%	36%	0%	100%	80%	5%	0%	99%	28%	0%	0%	99%	25%	0%	0%
August	100%	100%	100%	0%	100%	100%	99%	0%	100%	100%	47%	0%	100%	100%	33%	0%
September	100%	100%	87%	0%	100%	100%	77%	0%	100%	99%	57%	0%	100%	100%	55%	0%
October	36%	16%	0%	0%	34%	12%	0%	0%	33%	0%	0%	0%	33%	0%	0%	0%

Table C.6: Percent of days during critical periods (May through September) with temperature above the limit (2020) Gas Works Park 25ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	51%	0%	0%	0%	21%	0%	0%	0%	0%	0%	0%	0%	2%	0%	0%	0%
July	100%	65%	3%	0%	100%	34%	0%	0%	84%	7%	0%	0%	90%	3%	0%	0%
August	100%	100%	99%	0%	100%	100%	81%	0%	100%	100%	31%	0%	100%	99%	22%	0%
September	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	87%	0%	100%	100%	86%	0%
October	66%	48%	18%	0%	63%	46%	10%	0%	65%	40%	0%	0%	67%	40%	0%	0%

Table C.7: Percent of days during critical periods (May through September) with temperature above the limit (2018) Fremont Bridge 31ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	45%	0%	0%	0%	27%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%
July	100%	91%	46%	0%	100%	68%	28%	0%	94%	44%	0%	0%	60%	0%	0%	0%
August	100%	100%	100%	66%	100%	100%	100%	0%	100%	100%	83%	0%	100%	91%	38%	0%
September	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	87%	0%
October	74%	28%	6%	0%	75%	27%	5%	0%	73%	25%	5%	0%	69%	20%	0%	0%

Table C.8: Percent of days during critical periods (May through September) with temperature above the limit (2019) Fremont Bridge 31ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	22%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
July	100%	56%	17%	0%	83%	29%	0%	0%	39%	0%	0%	0%	32%	0%	0%	0%
August	100%	100%	100%	0%	100%	100%	89%	0%	100%	91%	46%	0%	100%	58%	4%	0%
September	100%	100%	90%	0%	100%	100%	81%	0%	100%	100%	79%	0%	100%	100%	36%	0%
October	40%	17%	0%	0%	39%	13%	0%	0%	33%	9%	0%	0%	33%	3%	0%	0%

Table C.9: Percent of days during critical periods (May through September) with temperature above the limit (2020) Fremont Bridge 31ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
July	94%	35%	0%	0%	62%	3%	0%	0%	28%	0%	0%	0%	10%	0%	0%	0%
August	100%	100%	85%	0%	100%	100%	61%	0%	100%	75%	17%	0%	100%	33%	0%	0%
September	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	0%	0%
October	72%	46%	32%	0%	71%	44%	29%	0%	71%	44%	2%	0%	69%	42%	0%	0%

Table C.10: Percent of days during critical periods (May through September) with temperature above the limit (2018) Fremont Bridge 40ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	45%	0%	0%	0%	34%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
July	100%	77%	46%	0%	100%	71%	0%	0%	71%	34%	0%	0%	0%	0%	0%	0%
August	100%	100%	100%	72%	100%	100%	92%	53%	100%	100%	77%	20%	90%	37%	8%	0%
September	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	67%	0%
October	83%	38%	7%	0%	82%	34%	5%	0%	76%	31%	3%	0%	68%	23%	0%	0%

Table C.11: Percent of days during critical periods (May through September) with temperature above the limit (2019) Fremont Bridge 40ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
July	58%	42%	14%	0%	41%	29%	0%	0%	21%	0%	0%	0%	0%	0%	0%	0%
August	100%	100%	100%	1%	100%	100%	77%	0%	100%	70%	50%	0%	66%	0%	0%	0%
September	100%	100%	94%	0%	100%	100%	91%	0%	100%	100%	88%	0%	100%	80%	0%	0%
October	46%	26%	0%	0%	43%	22%	0%	0%	40%	17%	0%	0%	33%	0%	0%	0%

Table C.12: Percent of days during critical periods (May through September) with temperature above the limit (2020) Fremont Bridge 40ft Depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
July	71%	6%	0%	0%	51%	4%	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%
August	100%	100%	89%	16%	100%	100%	45%	0%	100%	36%	16%	0%	54%	0%	0%	0%
September	100%	100%	89%	16%	100%	100%	100%	0%	100%	100%	99%	0%	100%	53%	0%	0%
October	70%	57%	39%	0%	70%	59%	15%	0%	71%	60%	0%	0%	69%	50%	0%	0%

Table C.13: Percent of days during critical periods (May through September) with temperature above the limit (2018) Ballard Bridge 21ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	16%	0%	0%	0%	15%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%
June	100%	57%	23%	0%	100%	46%	21%	0%	95%	38%	0%	0%	62%	26%	0%	0%
July	100%	100%	100%	35%	100%	100%	92%	28%	100%	100%	76%	15%	100%	97%	65%	0%
August	100%	100%	100%	86%	100%	100%	100%	85%	100%	100%	100%	84%	100%	100%	100%	75%
September	100%	100%	99%	0%	100%	100%	93%	0%	100%	100%	88%	0%	100%	100%	87%	0%
October	74%	26%	0%	0%	73%	24%	0%	0%	72%	22%	0%	0%	74%	22%	0%	0%

Table C.14: Percent of days during critical periods (May through September) with temperature above the limit (2019) Ballard Bridge 21ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	34%	0%	0%	0%	9%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	100%	73%	7%	0%	100%	65%	0%	0%	97%	54%	0%	0%	68%	0%	0%	0%
July	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	62%	0%	100%	97%	38%	0%
August	100%	100%	100%	89%	100%	100%	100%	80%	100%	100%	100%	10%	100%	100%	100%	0%
September	100%	100%	89%	33%	100%	100%	76%	24%	100%	100%	75%	1%	100%	100%	75%	0%
October	37%	19%	0%	0%	33%	11%	0%	0%	32%	9%	0%	0%	32%	8%	0%	0%

Table C.15: Percent of days during critical periods (May through September) with temperature above the limit (2020) Ballard Bridge 21ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	75%	22%	0%	0%	74%	19%	0%	0%	37%	0%	0%	0%	28%	0%	0%	0%
July	100%	100%	59%	0%	100%	100%	54%	0%	100%	81%	37%	0%	100%	59%	18%	0%
August	100%	100%	100%	96%	100%	100%	100%	91%	100%	100%	100%	56%	100%	100%	100%	5%
September	100%	100%	100%	70%	100%	100%	100%	64%	100%	100%	98%	7%	100%	100%	90%	4%
October	72%	42%	30%	0%	71%	39%	27%	0%	69%	34%	9%	0%	68%	34%	0%	0%

Table C.16: Percent of days during critical periods (May through September) with temperature above the limit (2018) Ballard Bridge 32ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	94%	24%	0%	0%	92%	22%	0%	0%	68%	13%	0%	0%	30%	0%	0%	0%
July	100%	100%	64%	5%	100%	100%	59%	0%	100%	100%	53%	0%	100%	75%	36%	0%
August	100%	100%	100%	75%	100%	100%	100%	68%	100%	100%	100%	48%	100%	100%	100%	1%
September	100%	100%	79%	0%	100%	100%	78%	0%	100%	100%	75%	0%	100%	100%	76%	0%
October	61%	28%	0%	0%	55%	25%	0%	0%	54%	16%	0%	0%	54%	14%	0%	0%

Table C.17: Percent of days during critical periods (May through September) with temperature above the limit (2019) Ballard Bridge 32ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	95%	44%	0%	0%	86%	35%	0%	0%	69%	19%	0%	0%	32%	0%	0%	0%
July	100%	100%	64%	0%	100%	100%	47%	0%	100%	100%	36%	0%	100%	60%	4%	0%
August	100%	100%	100%	9%	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	100%	0%
September	100%	100%	89%	0%	100%	100%	83%	0%	100%	100%	79%	0%	100%	100%	78%	0%
October	32%	15%	0%	0%	32%	12%	0%	0%	31%	8%	0%	0%	30%	8%	0%	0%

Table C.18: Percent of days during critical periods (May through September) with temperature above the limit (2020) Ballard Bridge 32ft depth.

	Baseline Model				Scenario 1B Model				Scenario 2 Model				Scenario 3 Model			
	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C	16°C	17.5°C	19°C	22°C
May	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
June	31%	0%	0%	0%	25%	0%	0%	0%	16%	0%	0%	0%	0%	0%	0%	0%
July	100%	82%	27%	0%	100%	73%	22%	0%	100%	54%	9%	0%	93%	33%	0%	0%
August	100%	100%	100%	57%	100%	100%	100%	27%	100%	100%	100%	0%	100%	100%	97%	0%
September	100%	100%	88%	32%	100%	100%	87%	14%	100%	100%	86%	1%	100%	95%	85%	0%
October	76%	53%	0%	0%	76%	48%	0%	0%	75%	42%	0%	0%	74%	33%	0%	0%

C.3 Salinity Results

C.3.1 University Bridge Salinity Results

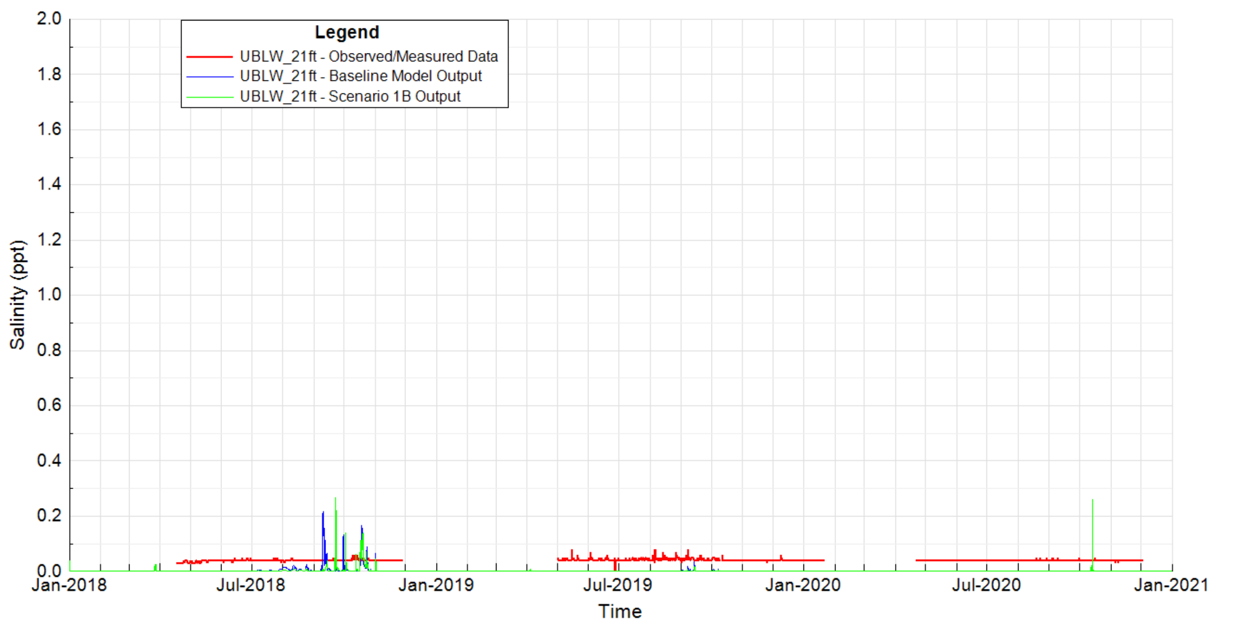

Figure C.19: Salinity output comparison over time, 2018 - 2021: University Bridge-21ft depth Scenario 1B.

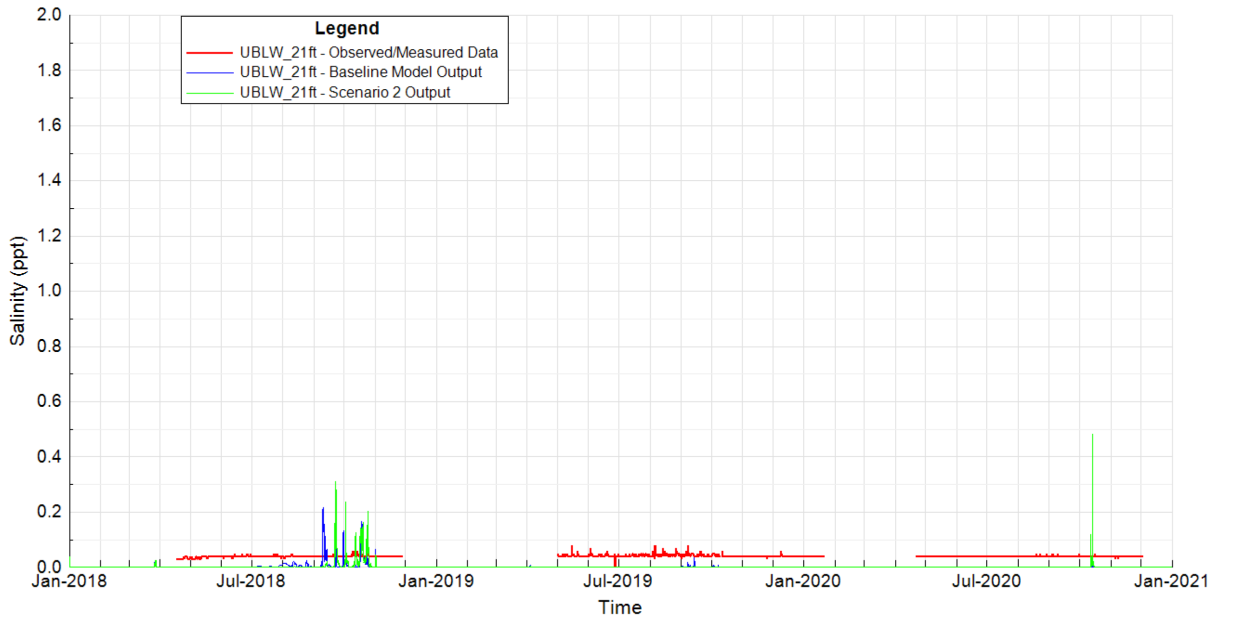

Figure C.20: Salinity output comparison over time, 2018 - 2021: University Bridge-21ft depth Scenario 2.

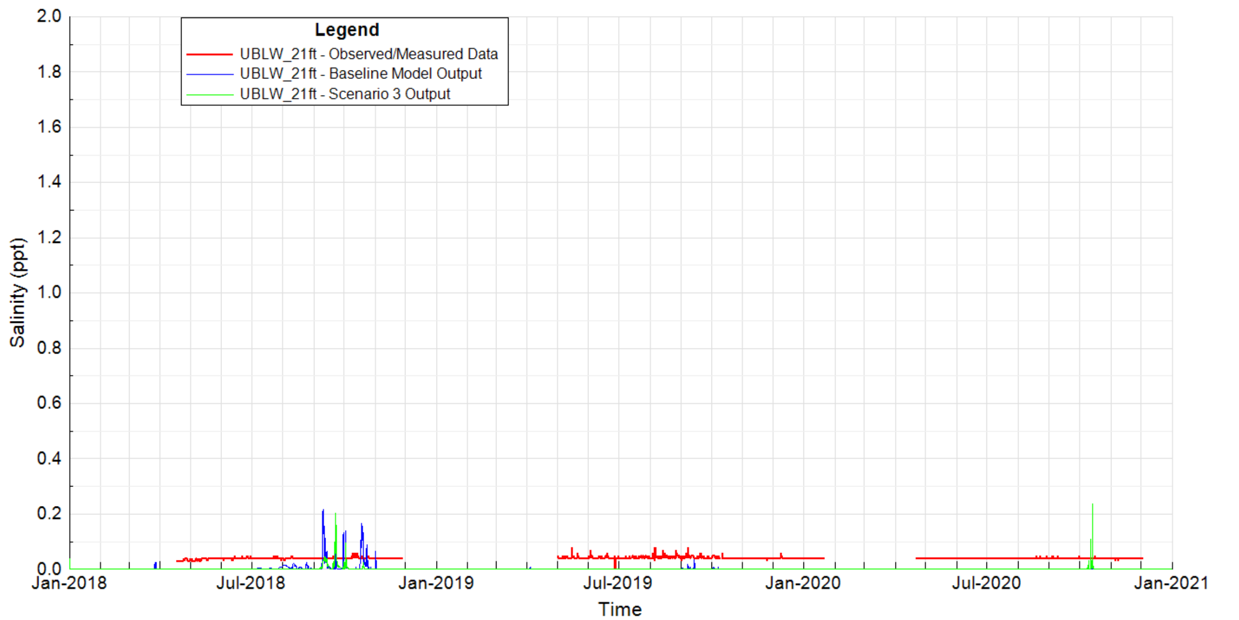

Figure C.21: Salinity output comparison over time, 2018 - 2021: University Bridge-21ft depth Scenario 3.

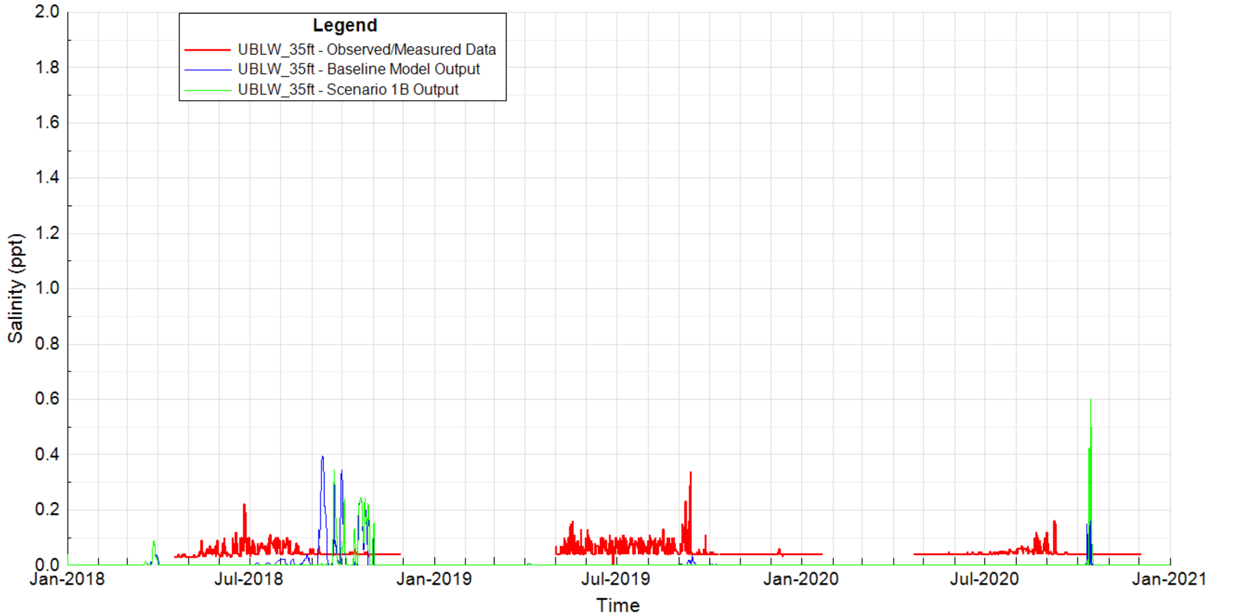

Figure C.22: Salinity output comparison over time, 2018 - 2021: University Bridge-35ft depth Scenario 1B.

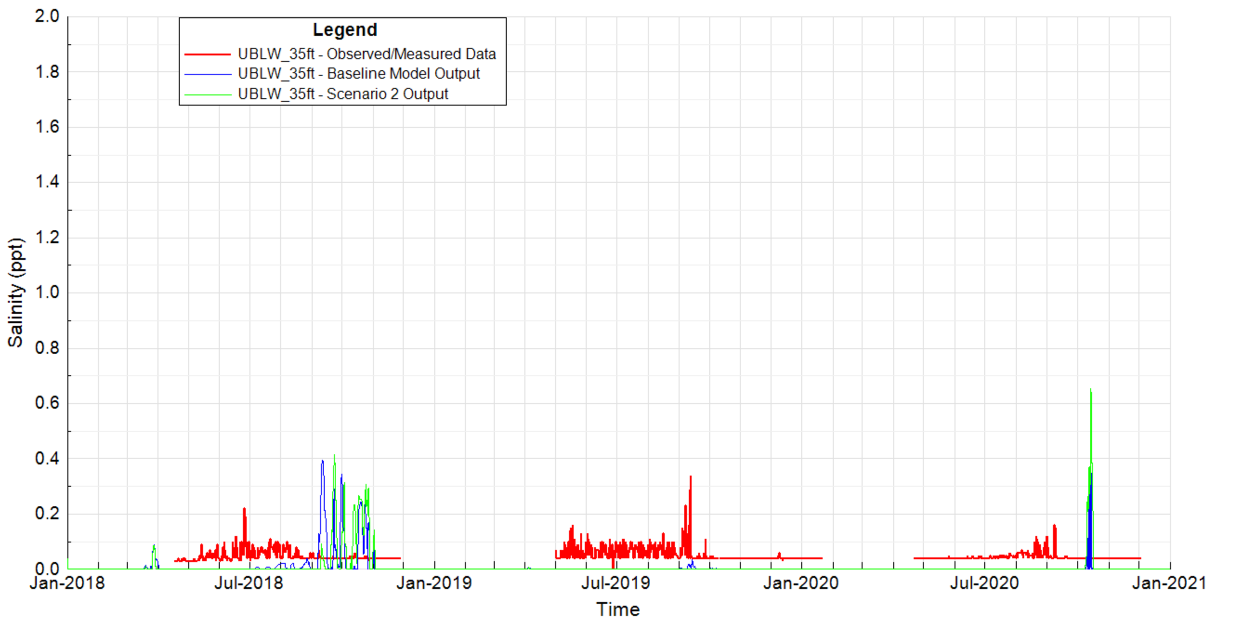

Figure C.23: Salinity output comparison over time, 2018 - 2021: University Bridge-35ft depth Scenario 2.

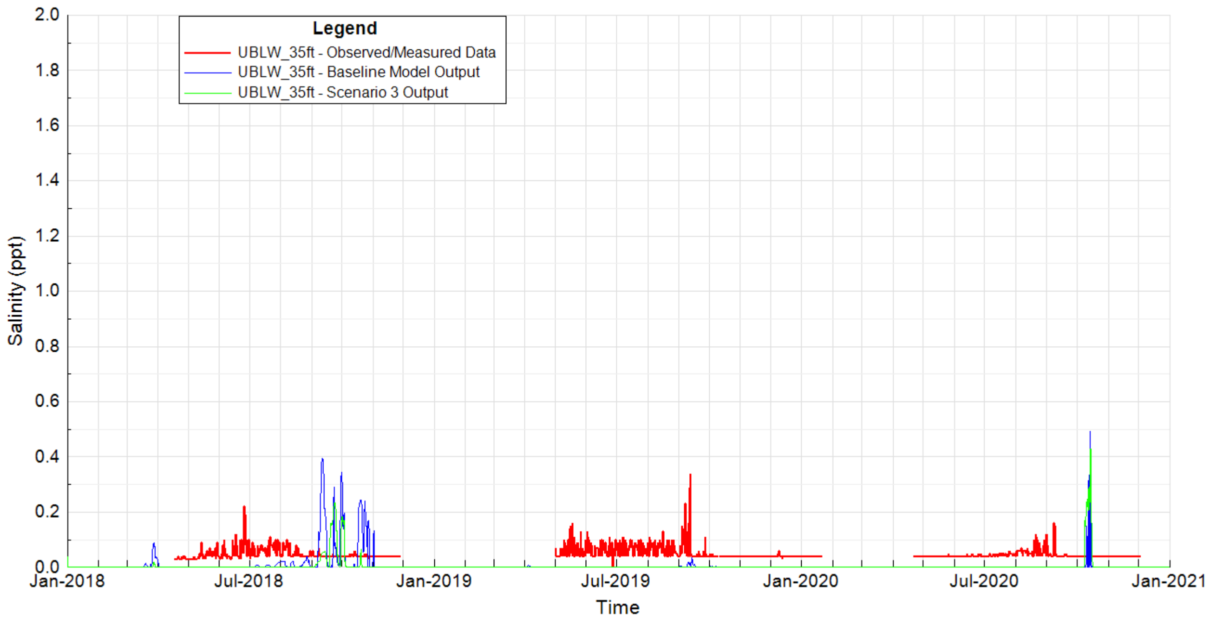

Figure C.24: Salinity output comparison over time, 2018 - 2021: University Bridge-35ft depth Scenario 3.

C.3.2 Gas Works Park Salinity Results

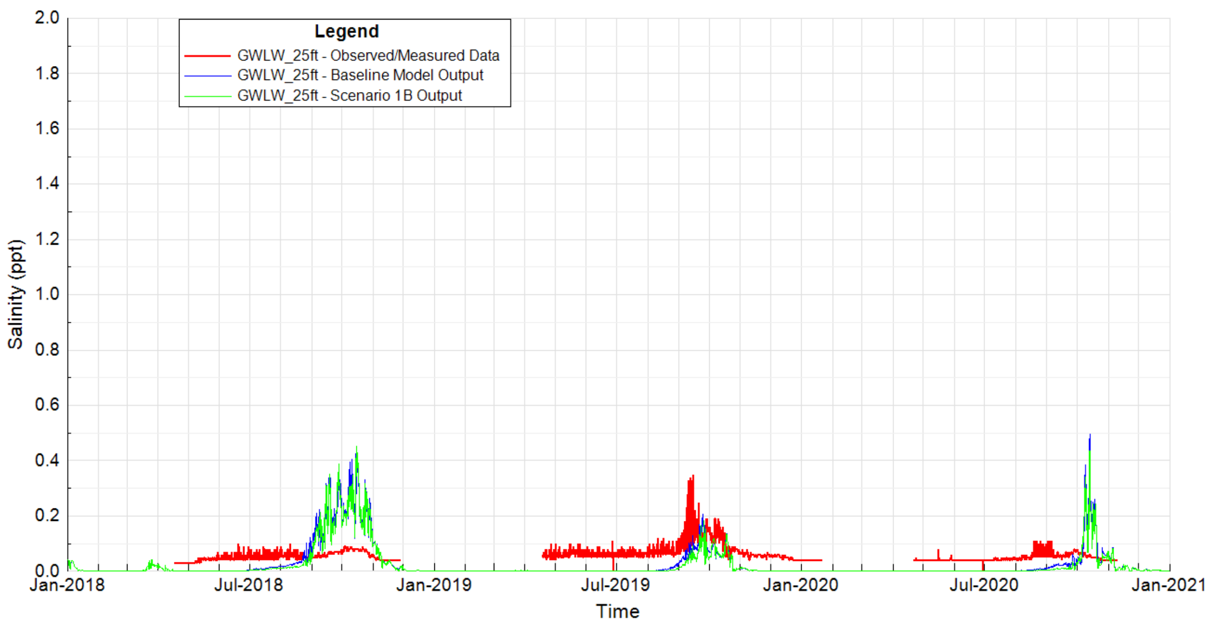

Figure C.25: Salinity output comparison over time, 2018 - 2021: Gas Works Park-25ft depth Scenario 1B.

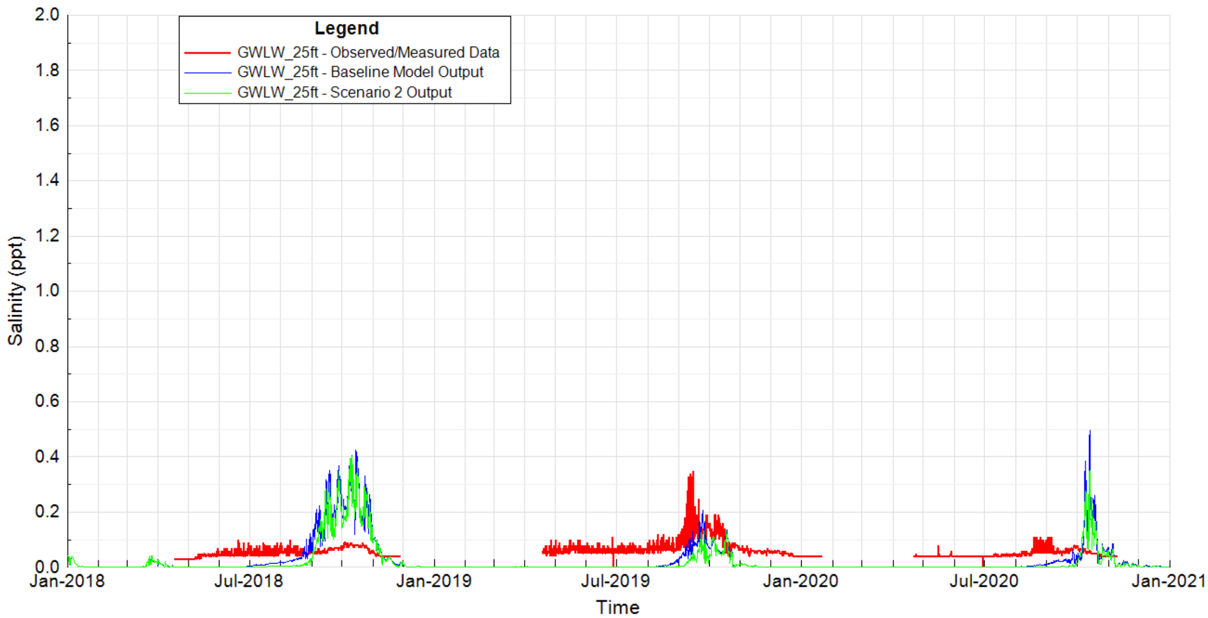

Figure C.26: Salinity output comparison over time, 2018 - 2021: Gas Works Park-25ft depth Scenario 2.

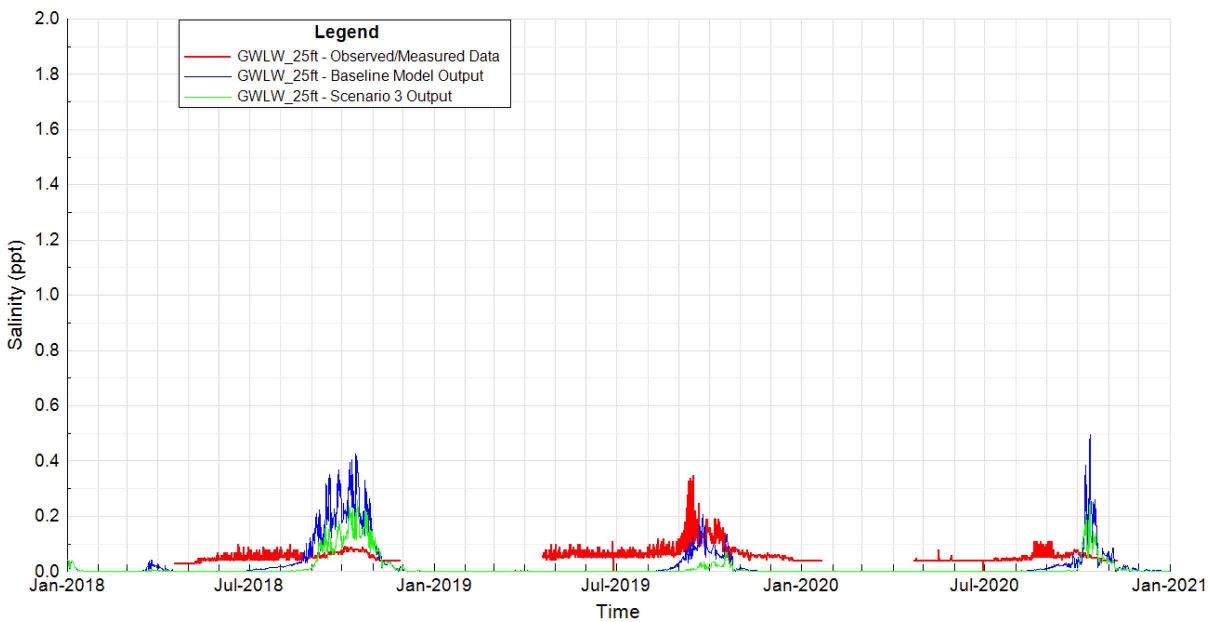

Figure C.27: Salinity output comparison over time, 2018 - 2021: Gas Works Park-25ft depth Scenario 3.

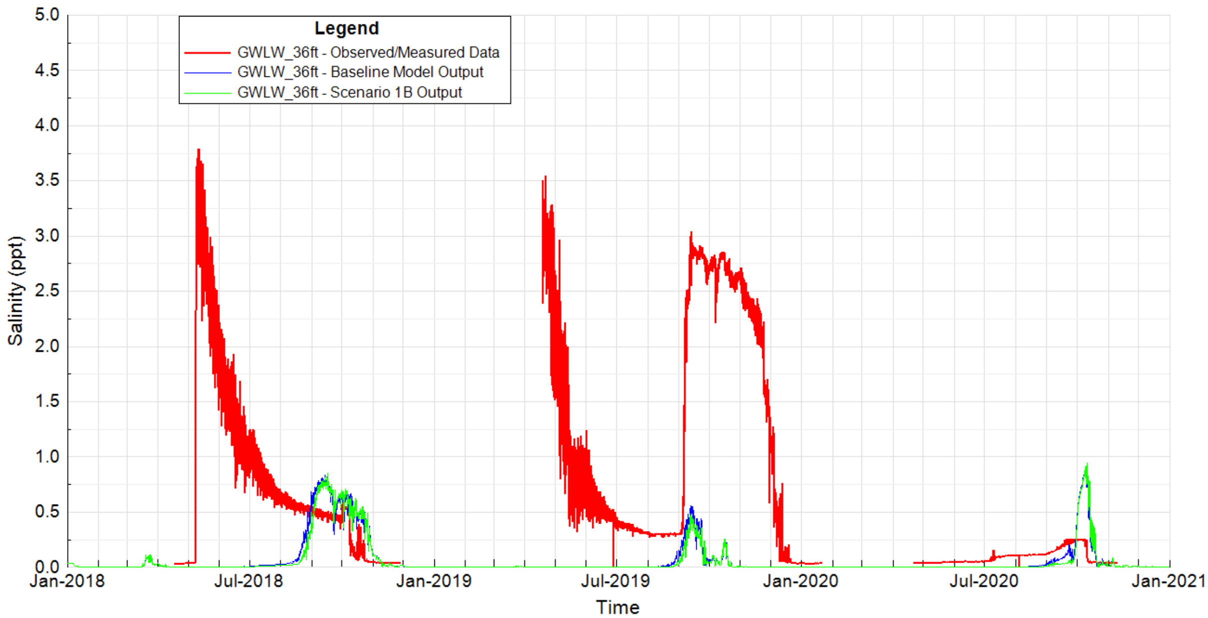

Figure C.28: Salinity output comparison over time, 2018 - 2021: Gas Works Park-36ft depth Scenario 1B.

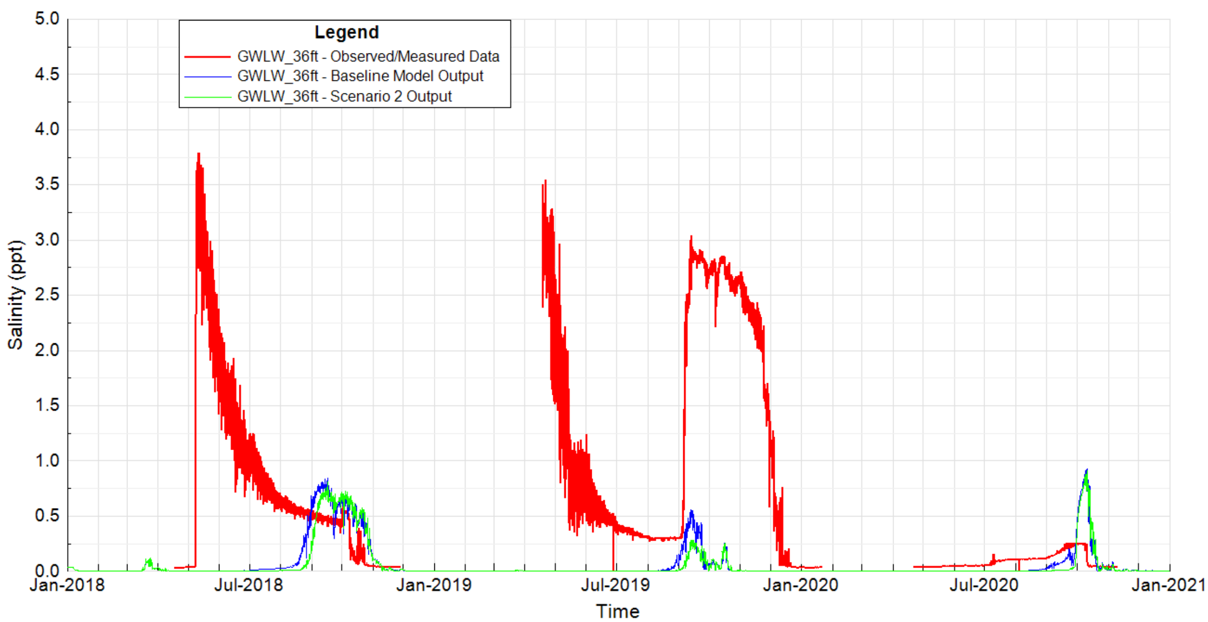

Figure C.29: Salinity output comparison over time, 2018 - 2021: Gas Works Park-36ft depth Scenario 2.

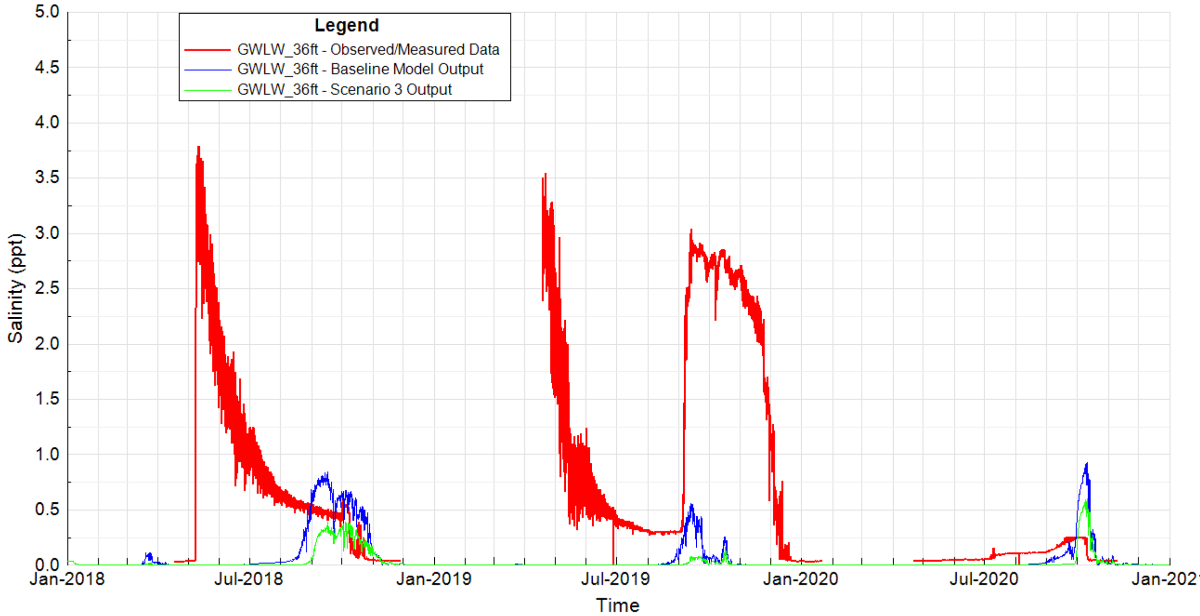

Figure C.30: Salinity output comparison over time, 2018 - 2021: Gas Works Park-36ft depth Scenario 3.

C.3.3 Fremont Bridge Salinity Results

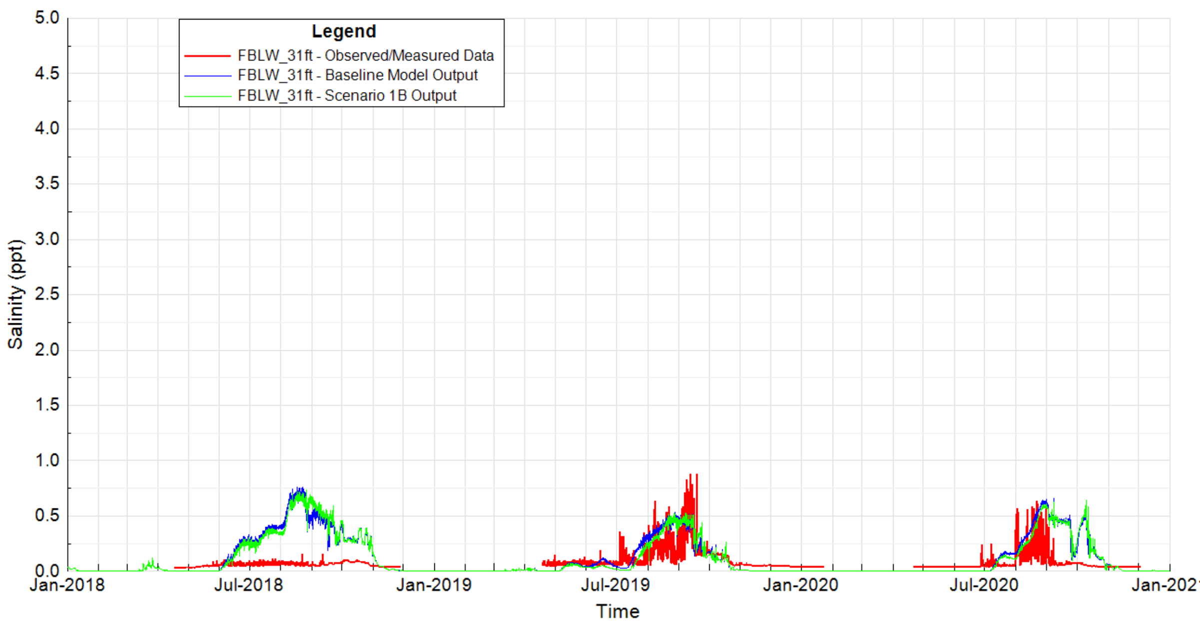

Figure C.31: Salinity output comparison over time, 2018 - 2021: Fremont Bridge-31ft depth Scenario 1B.

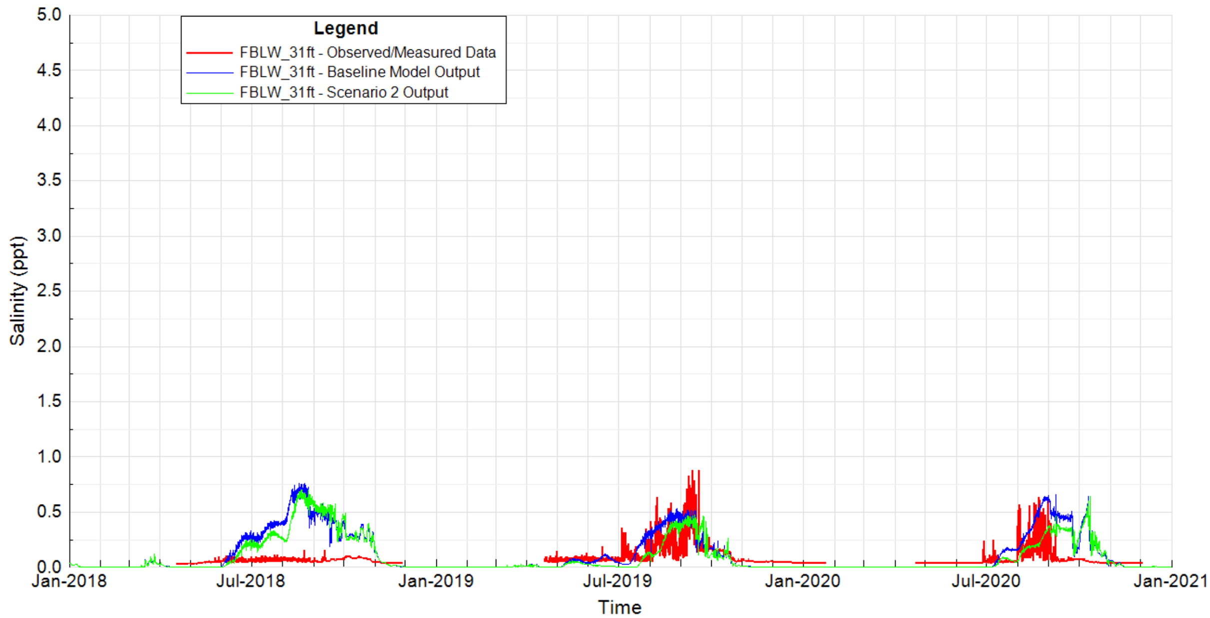

Figure C.32: Salinity output comparison over time, 2018 - 2021: Fremont Bridge-31ft depth Scenario 2.

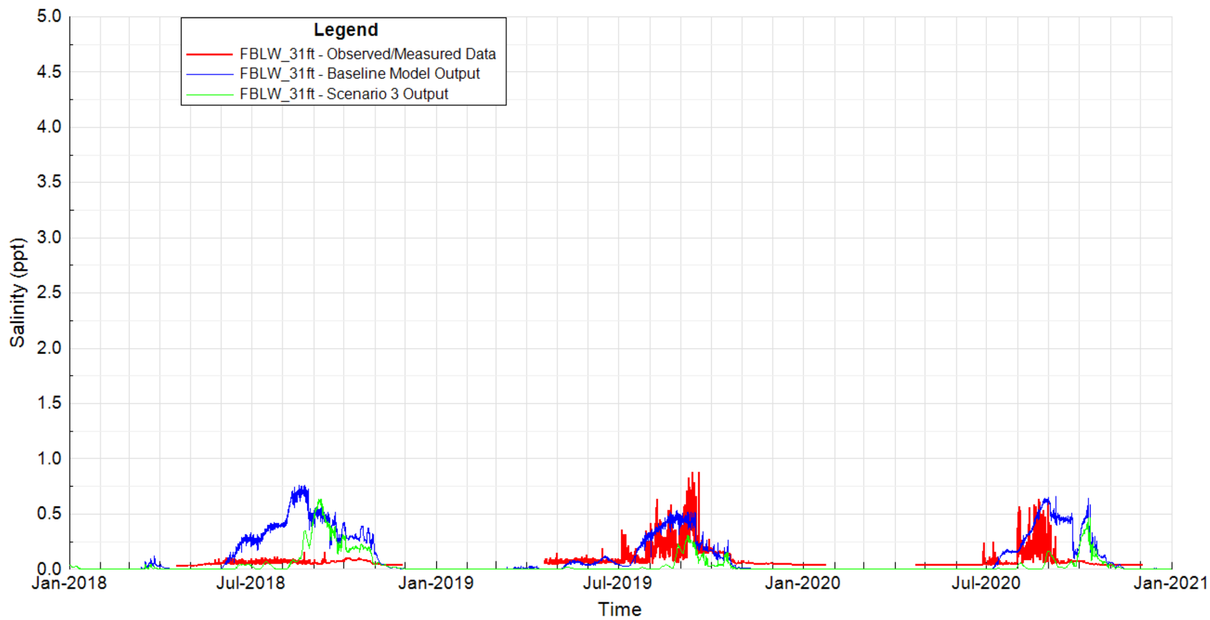

Figure C.33: Salinity output comparison over time, 2018 - 2021: Fremont Bridge-31ft depth Scenario 3.

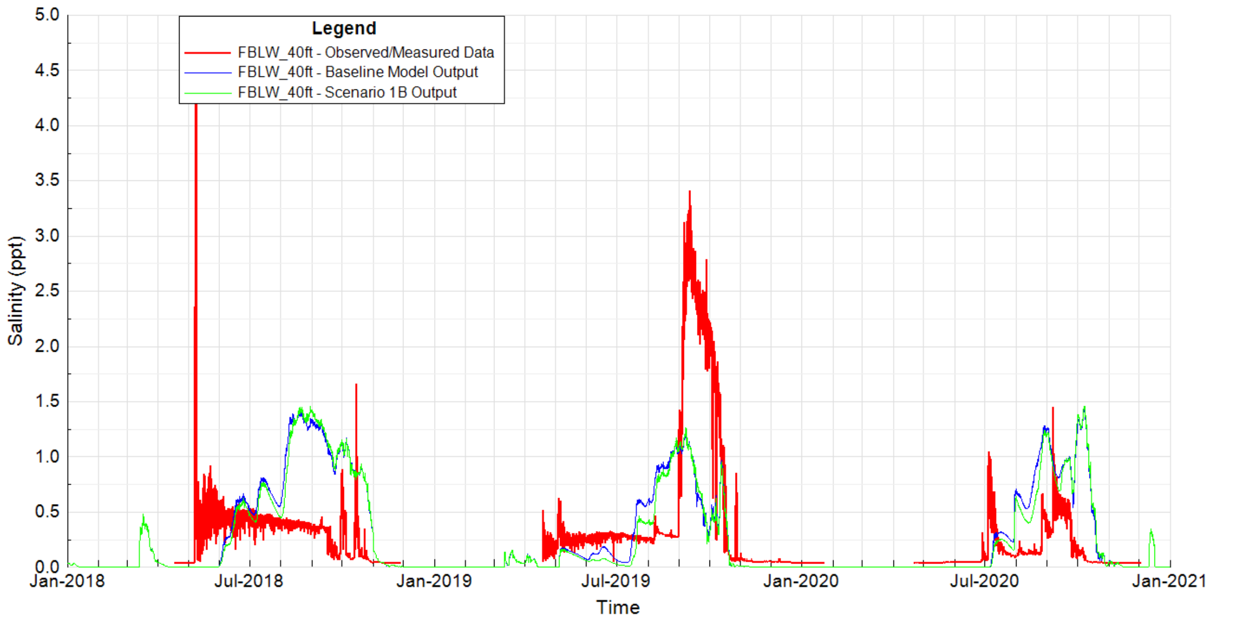

Figure C.34: Salinity output comparison over time, 2018 - 2021: Fremont Bridge-40ft depth Scenario 1B.

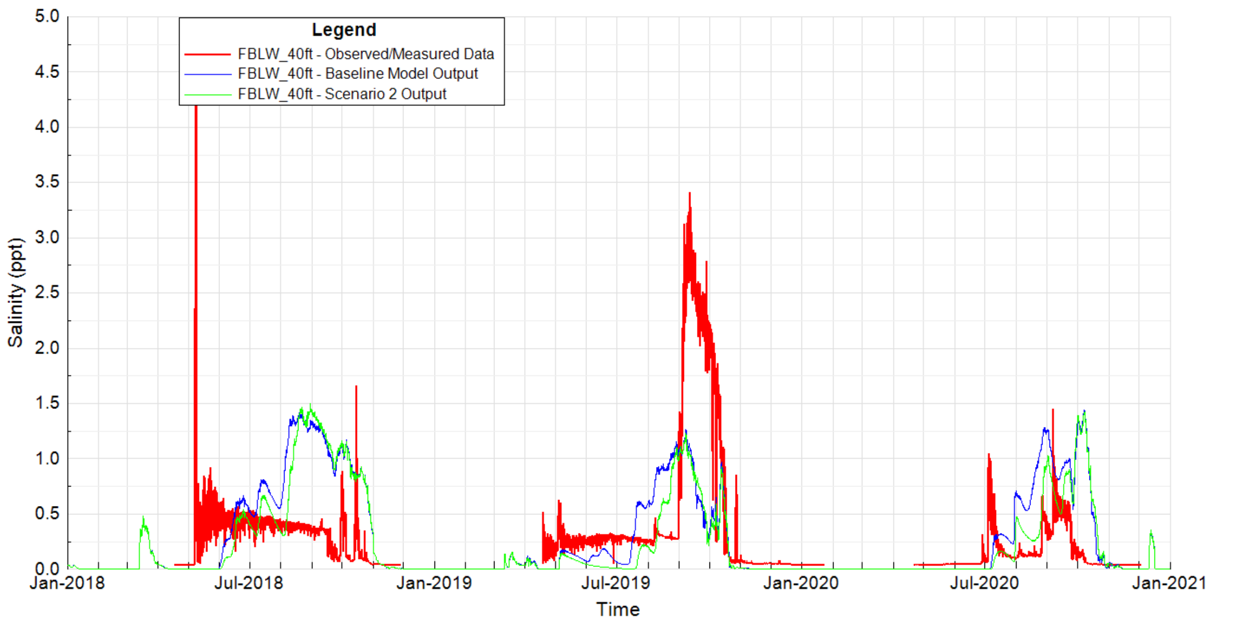

Figure C.35: Salinity output comparison over time, 2018 - 2021: Fremont Bridge-40ft depth Scenario 2.

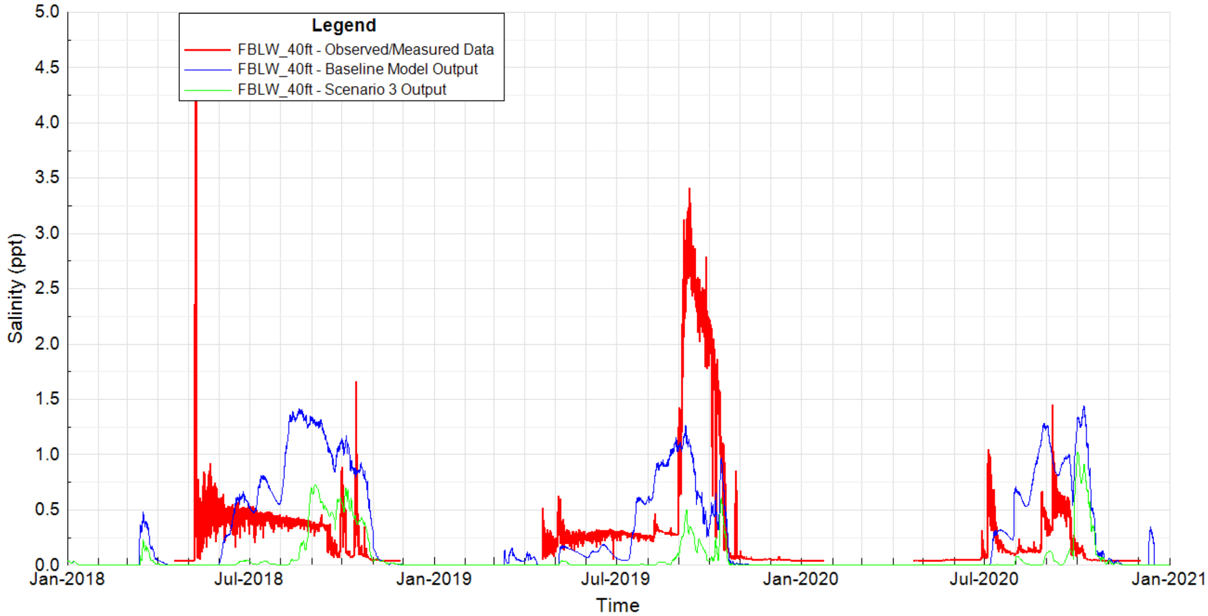

Figure C.36: Salinity output comparison over time, 2018 - 2021: Fremont Bridge-40ft depth Scenario 3.

C.3.4 Ballard Bridge Salinity Results

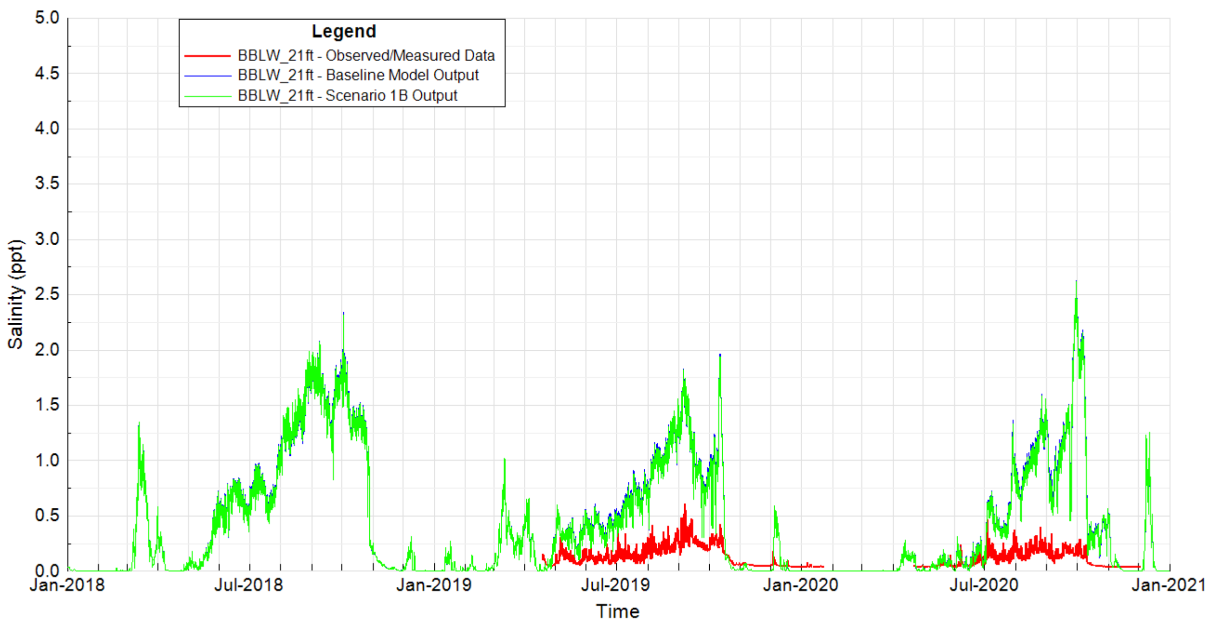

Figure C.37: Salinity output comparison over time, 2018 - 2021: Ballard Bridge-21ft depth Scenario 1B.

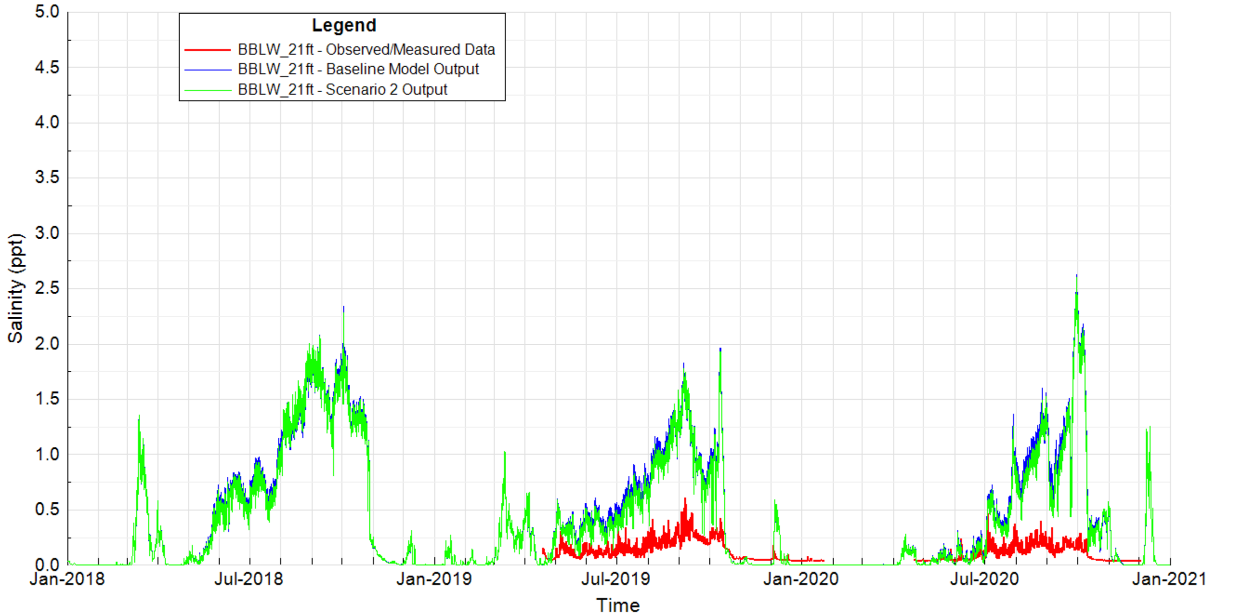

Figure C.38: Salinity output comparison over time, 2018 - 2021: Ballard Bridge-21ft depth Scenario 2.

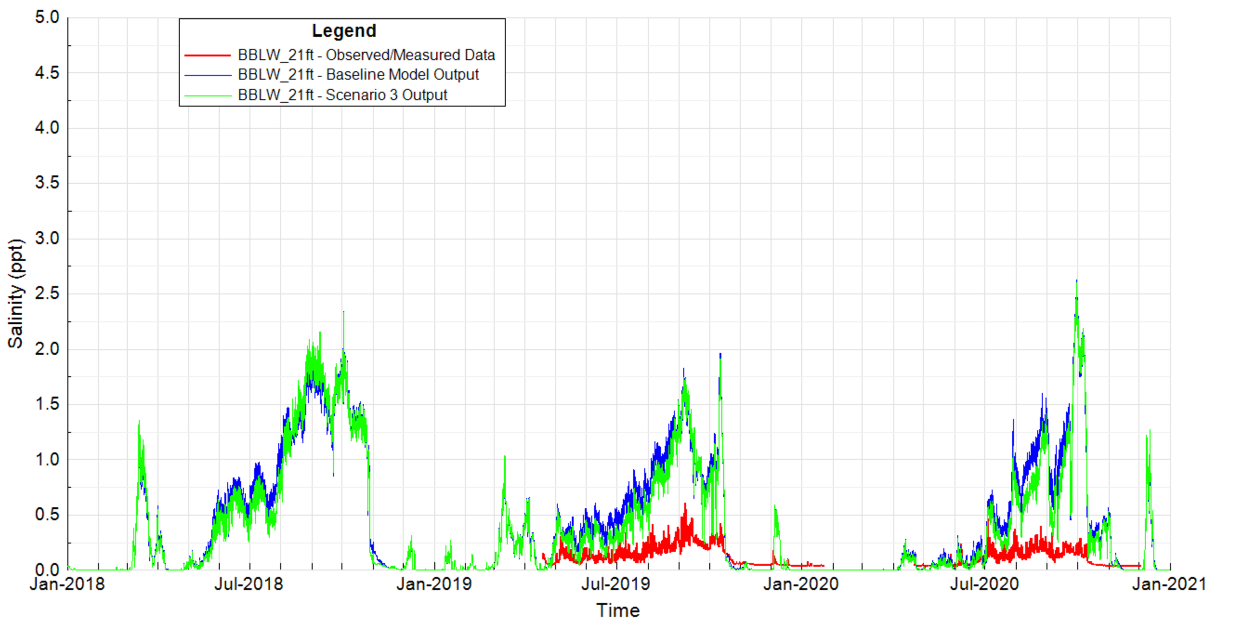

Figure C.39: Salinity output comparison over time, 2018 - 2021: Ballard Bridge-21ft depth Scenario 3.

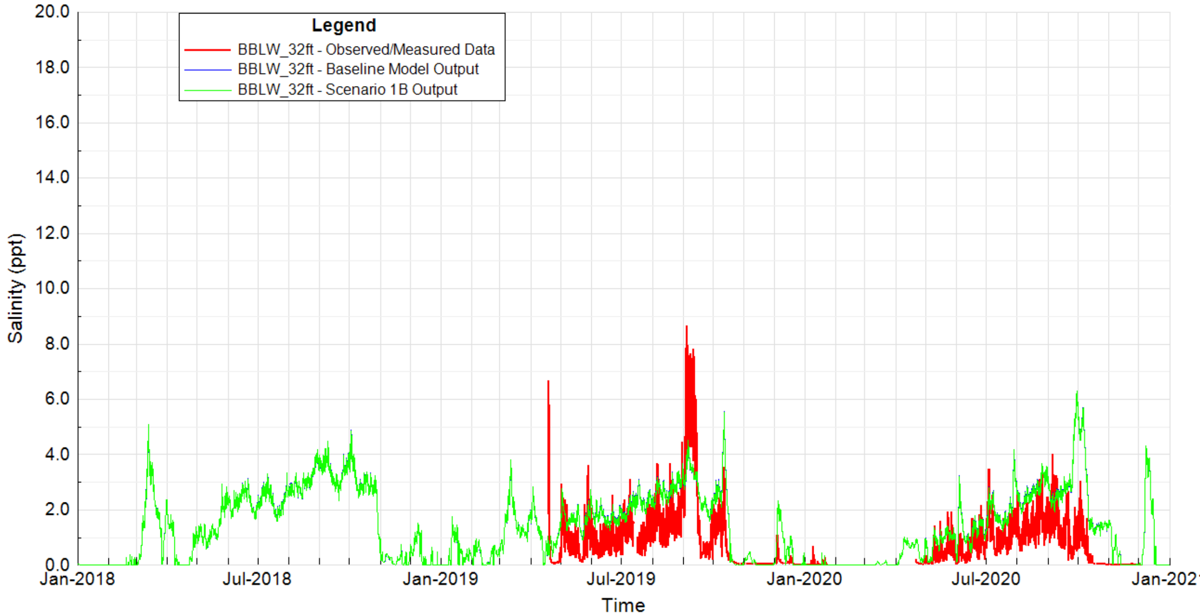

Figure C.40: Salinity output comparison over time, 2018 - 2021: Ballard Bridge-32ft depth Scenario 1B.

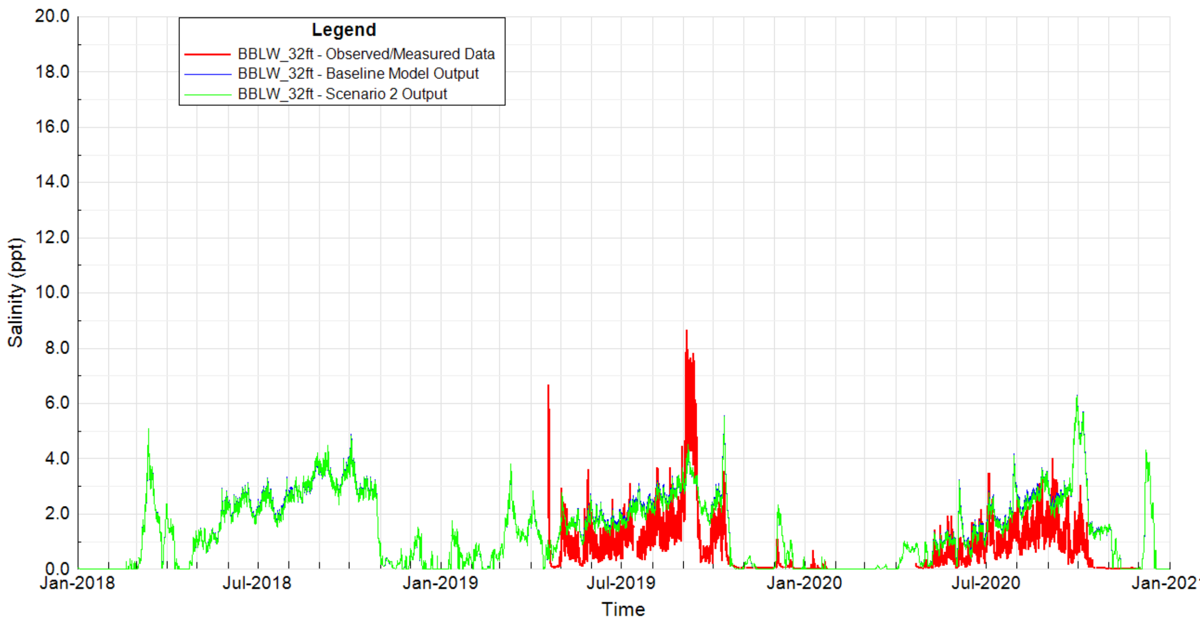

Figure C.41: Salinity output comparison over time, 2018 - 2021: Ballard Bridge-32ft depth Scenario 2.

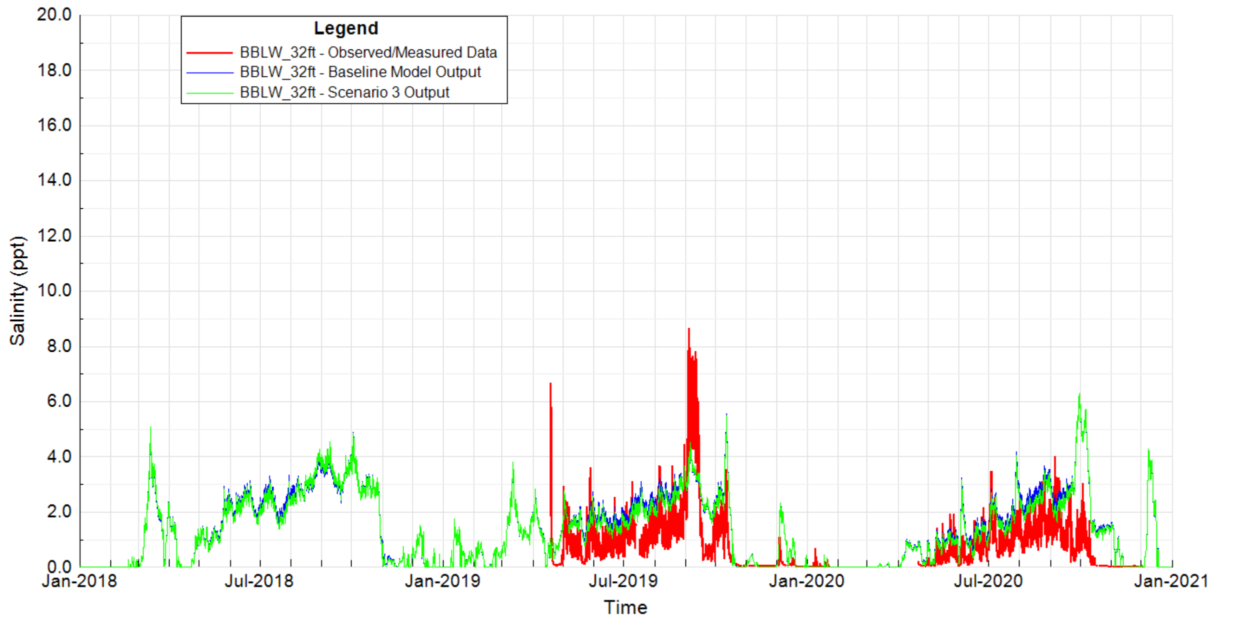

Figure C.42: Salinity output comparison over time, 2018 - 2021: Ballard Bridge-32ft depth Scenario 3.

C.3.5 Large Lock Salinity Results

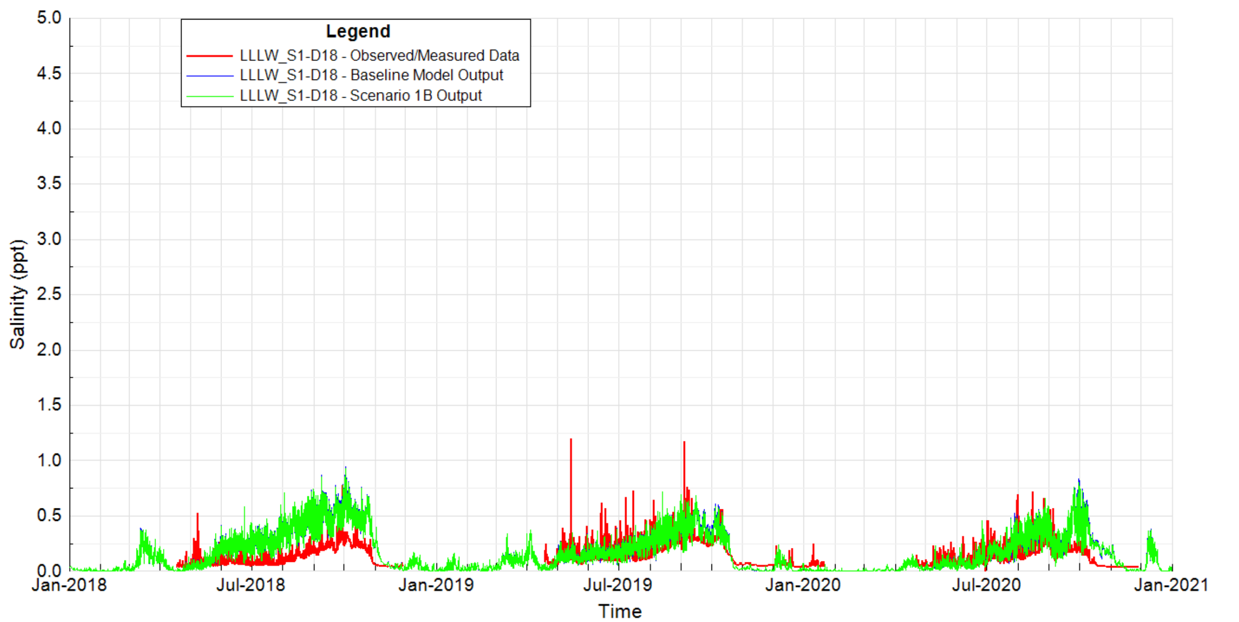

Figure C.43: Salinity output comparison over time, 2018 - 2021: Large Lock-18ft depth Scenario 1B.

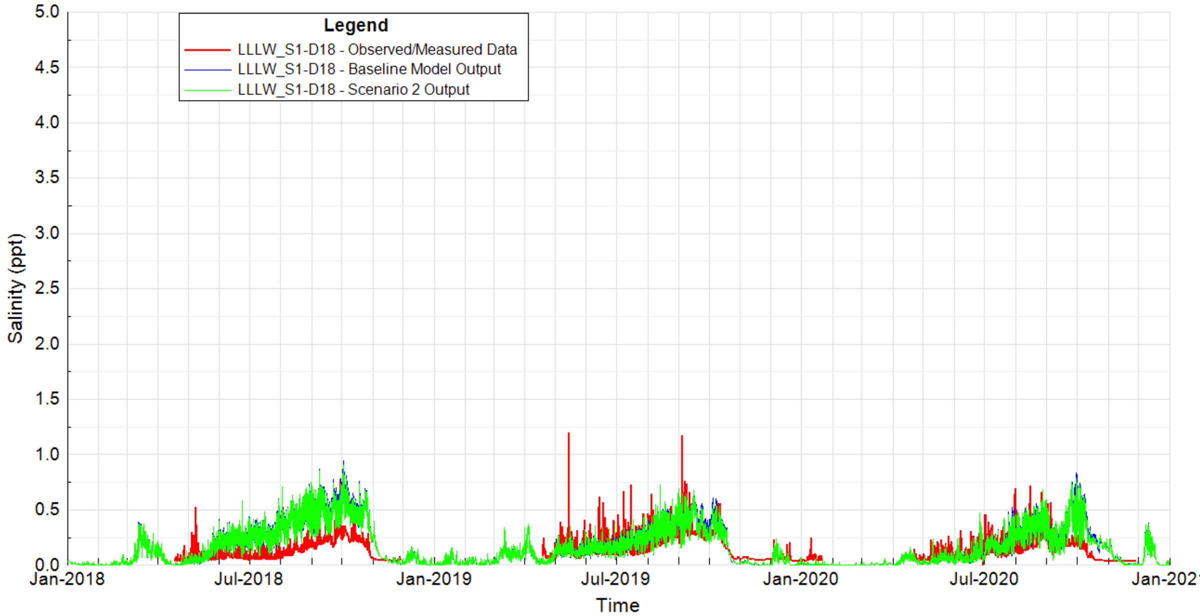

Figure C.44: Salinity output comparison over time, 2018 - 2021: Large Lock-18ft depth Scenario 2.

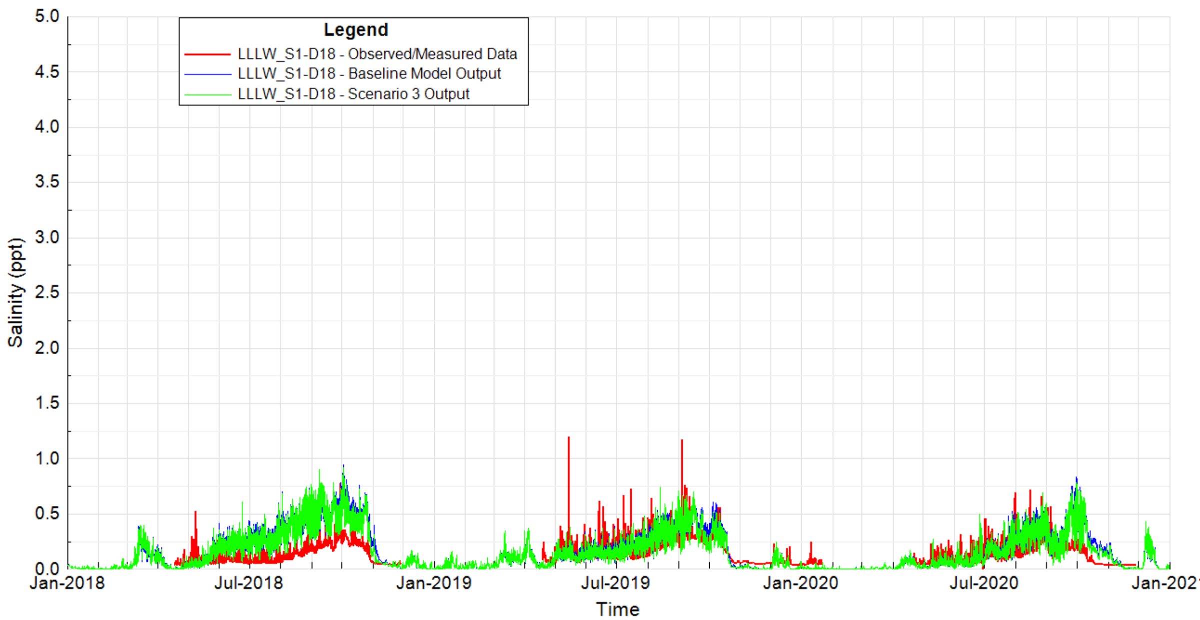

Figure C.45: Salinity output comparison over time, 2018 - 2021: Large Lock-18ft depth Scenario 3.

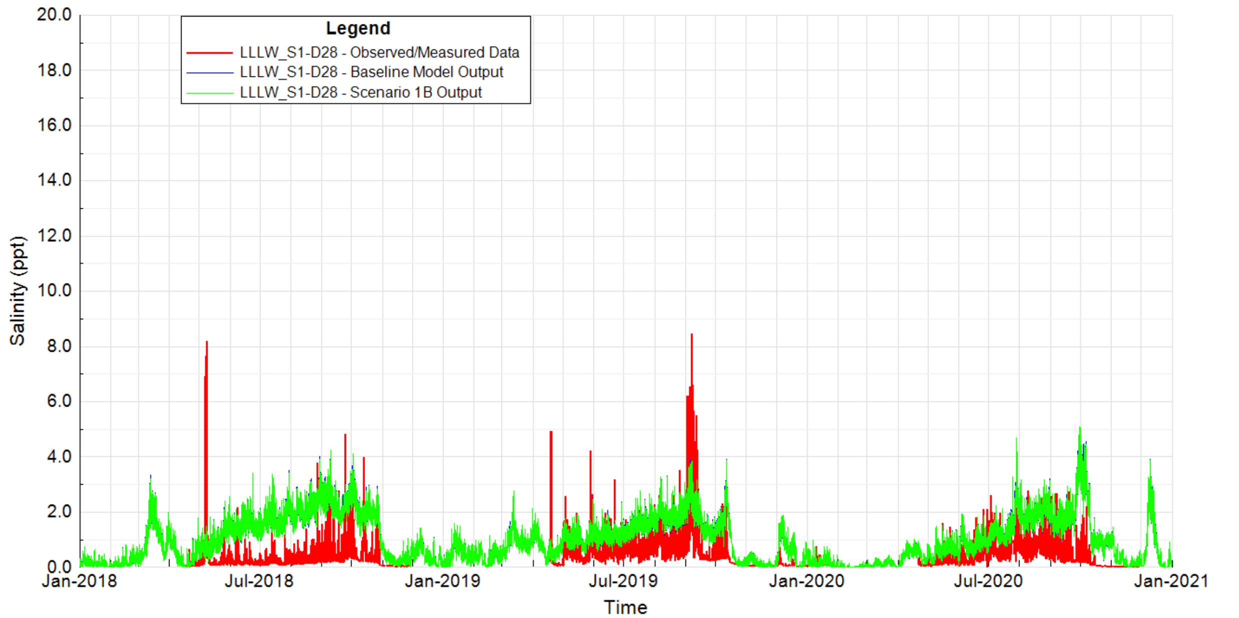

Figure C.46: Salinity output comparison over time, 2018 - 2021: Large Lock-28ft depth Scenario 1B.

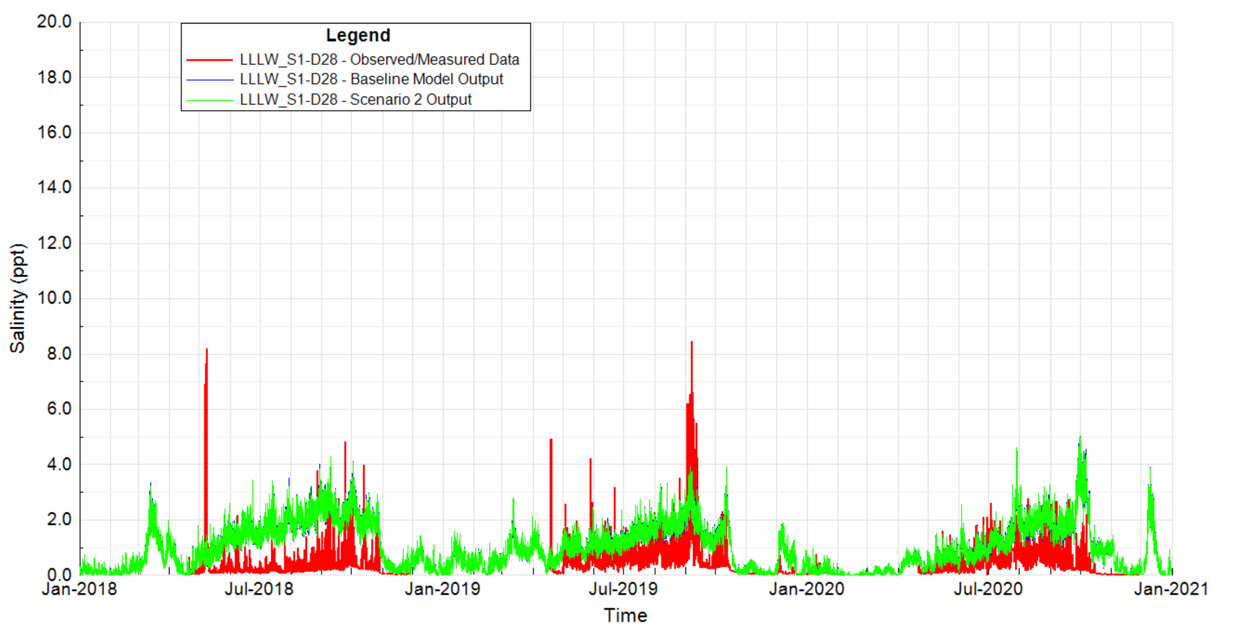

Figure C.47: Salinity output comparison over time, 2018 - 2021: Large Lock-28ft depth Scenario 2.

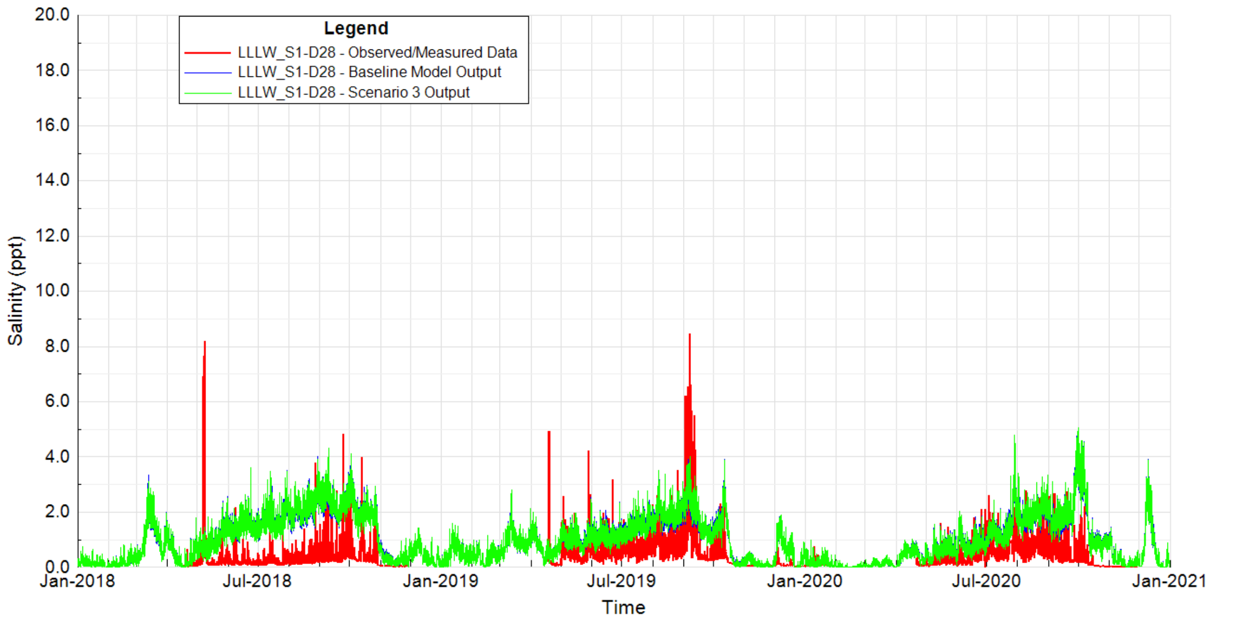

Figure C.48: Salinity output comparison over time, 2018 - 2021: Large Lock-28ft depth Scenario 3.

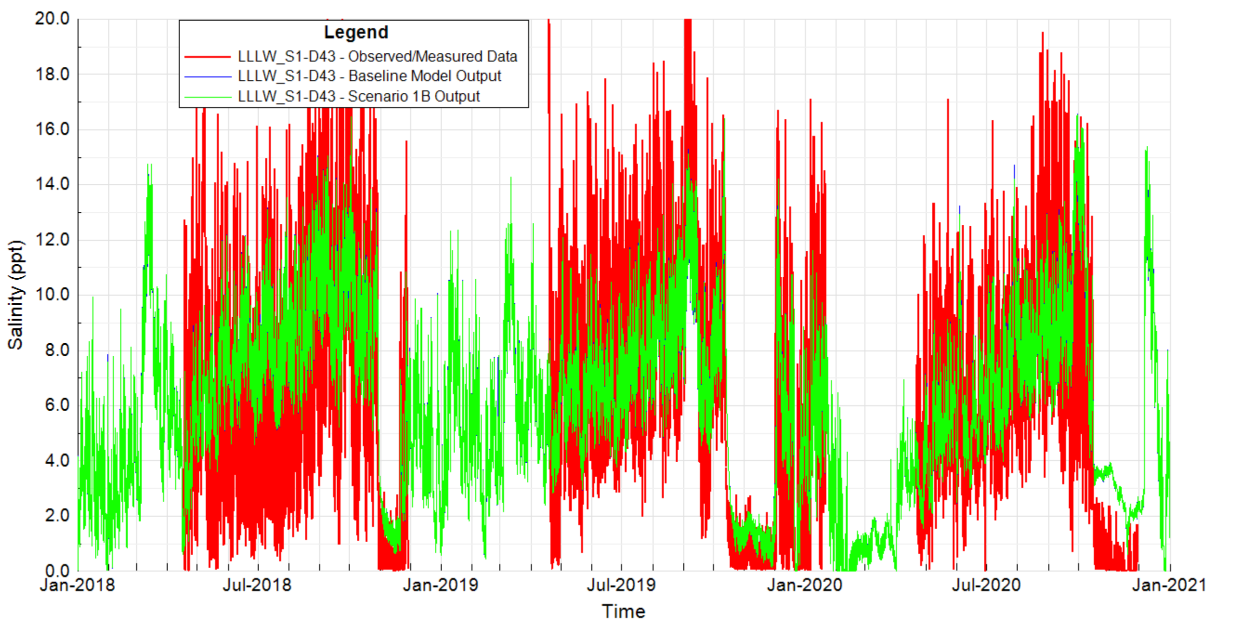

Figure C.49: Salinity output comparison over time, 2018 - 2021: Large Lock-43ft depth Scenario 1B.

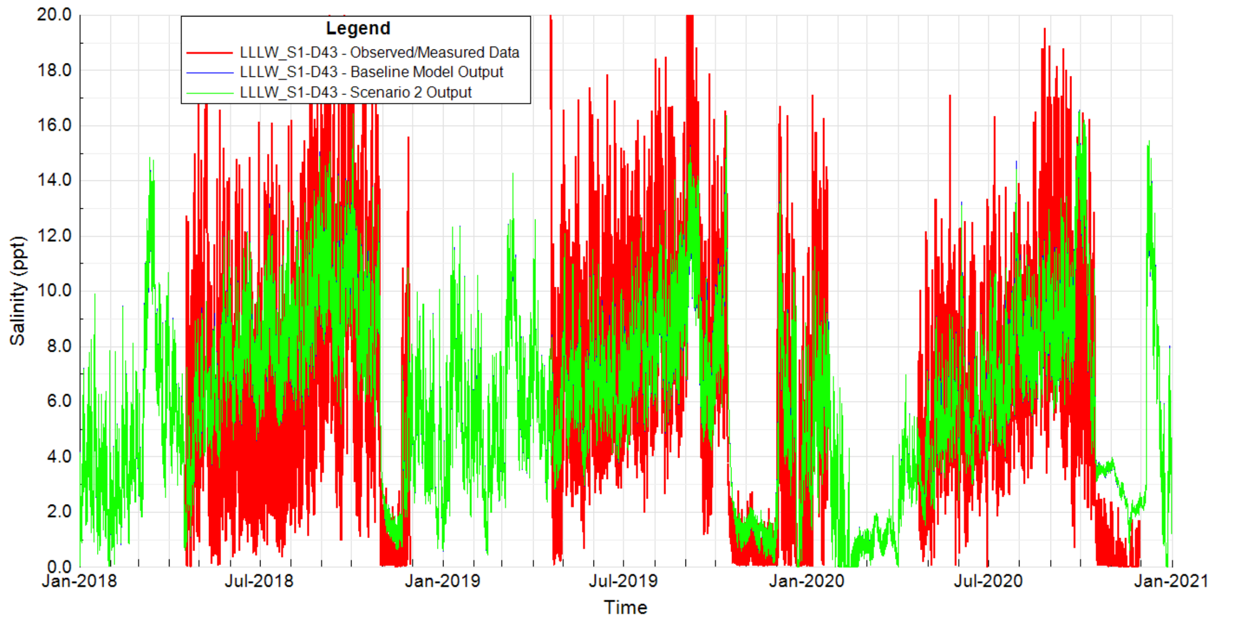

Figure C.50: Salinity output comparison over time, 2018 - 2021: Large Lock-43ft depth Scenario 2.

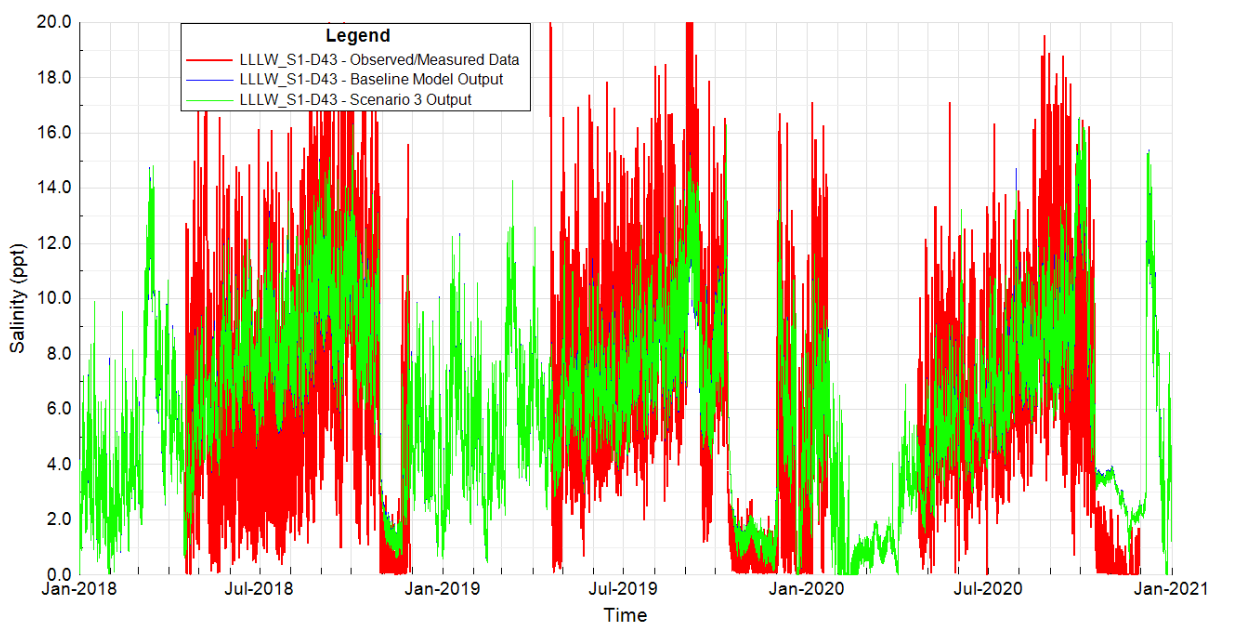

Figure C.51: Salinity output comparison over time, 2018 - 2021: Large Lock-43ft depth Scenario 3.

D QUALITY ASSURANCE PROJECT PLAN

D.1 Introduction

This Quality Assurance Project Plan (QAPP) documents the systematic planning process to be used for the Lake Washington Ship Canal (LWSC) Model project, following the guidance promulgated by the United States Environmental Protection Agency (USEPA) (USEPA, 2002). The QAPP includes the following key elements:

- Description of the project, goals, and objective;
- Project organization, responsible personnel, and schedule;
- Data quality objectives for measured and modeled data;
- Model framework to support the project goals and objectives;
- Data collection and acquisition to support model build and calibration;
- Specification of quality assurance/quality control (QA/QC) activities to assess the performance criteria for EFDC;
- Model usability assessment; and
- Project reporting.

D.1.1 Project Description

Salmon are integral to the cultures, livelihoods, ecosystems, and tribal treaty rights in the Lake Washington/Cedar/Sammamish Watershed (Water Resource Inventory Area [WRIA] 8). Many salmon populations in the watershed have declined in recent decades due to myriad factors. During migration windows, lethal and sublethal temperature and dissolved oxygen (DO) conditions in the LWSC represent key obstacles to salmon recovery. The LWSC connects the saltwater Puget Sound (Shilshole Bay) to freshwater Lake Washington (Union Bay) via the Hiram M. Chittenden Locks, Salmon Bay, the Fremont Cut, Lake Union, Portage Bay, and the Montlake Cut (Figure D.1). It is a heavily used, unique, and highly engineered system central to the most populous watershed in Washington State. Salmon are anadromous, living part of their life cycle in fresh water and part in salt water; all salmon in the watershed must pass through the LWSC twice in their lifetimes, as out-migrating juveniles and as returning adults.

Water temperature is a primary determinant of salmon health, development, migration, and survival. Heat-stressed salmon face increased risks from parasites, infection, predation, and migration blockages or delays which can result in increased mortality rates and reduced spawning success (Urgenson, Kudo, and DeGasperi, 2021). Predatory fish species in the LWSC have a higher metabolism at warmer temperatures, allowing them to capture smolts more efficiently and digest them more quickly. Delayed migration due to high temperatures is of particular concern for juveniles that migrate through the LWSC and adult Chinook and coho salmon, which will hold just upstream of the Locks.

Long Live the Kings (LLTK) is testing the hypothesis that cold water inputs to the LWSC can improve water quality for the benefit of juvenile and adult salmon. As this report describes, to evaluate the effectiveness of this concept in reducing the potential for heat stress on migrating salmon, DSI, LLC (DSI) refined an existing 3-dimensional hydrodynamic model of Lake Washington, Lake Union, and the LWSC it had previously developed. Proposed cold water inputs were iteratively adjusted to describe potential changes to LWSC temperatures and salinity. A group of technical experts can then use this information to provide inputs on the likely benefits to salmon.

Based on the Synthesis Report prepared by King County WRIA8, several temperature milestones have been established (Urgenson, Kudo, and DeGasperi, 2021). A desired outcome of this project is to develop one or more scenarios that produce consistent (*i.e.*, 95% of the time) temperatures localized to the bottom layer or through the water column below the following thresholds:

- Lethal Conditions per King County Synthesis Report: 22° C
- Temperature Allowing Fish Passage Based on Tracking Data: 19° C
- Temperature Required for Salmonid Rearing and Migration Only: 17.5° C
- Core Temperature for Summer Salmonid Habitat: 16° C

D.1.2 Project Goals and Objectives

The project aims to evaluate the potential for significantly reducing thermal barriers to fish passage in the LWSC through an expanded cold-water injection project. While largely hypothetical at this stage, this study intends to help further define the necessary scale of any future project(s) that may come about to meet these ambitious goals.

Under the project scope of work, we performed the following general tasks:

1. Develop a QAPP, conforming to general best practices and applicable guidance from USEPA;

2. Using an existing model of Lake Washington developed by DSI, add local wind and meteorological data from the LWSC, as available, and recalibrate the baseline model using existing monitoring stations shown in Figure 3.4;

3. Include more detailed information on Lock operations from the USACE to improve the capability of the LWSC Model in Salmon Bay;

4. Prepare a report on the current baseline LWSC Model (*i.e.*, existing conditions), including model boundary conditions, parameter configurations, calibration, and validation;

5. Develop and document a scenario reflecting proposed cold-water injection points at the University of Washington (UW) and Seattle Pacific University (SPU), including estimates of flow rate, temperature, salinity, and proposed location for two cold-water injection sites based on input from dJoule;

6. Develop additional scenarios with input from LLTK, King County, and other stakeholders as requested. Based on feedback to date, this may include evaluations of the potential long-term temperature and salinity impacts of cold-water injection on the Lake Union and LWSC system; and

7. Preparation of a Final Project Report.

D.2 Project Management

Thomas Mathis and Kester Scandrett are the key DSI team members responsible for ensuring the project meets all QA and QC objectives. The DSI personnel and schedule for the project are described below.

D.2.1 Project Organization

Table D.1 lists the project personnel and responsibilities. The project team members are described briefly below.

Thomas Mathis is DSI's Operations Manager for this project. His role is to provide general project oversight and interact with LLTK and other stakeholders, overseeing the data and model management of the project and perform data QA/QC prior to model inputs being provided for simulation. He is the primary point of contact for DSI and the project.

Kester Scandrett is DSI's General Manager for this project. His role is to oversee day-to-day tasks for the project and provide preliminary QA/QC of data and models.

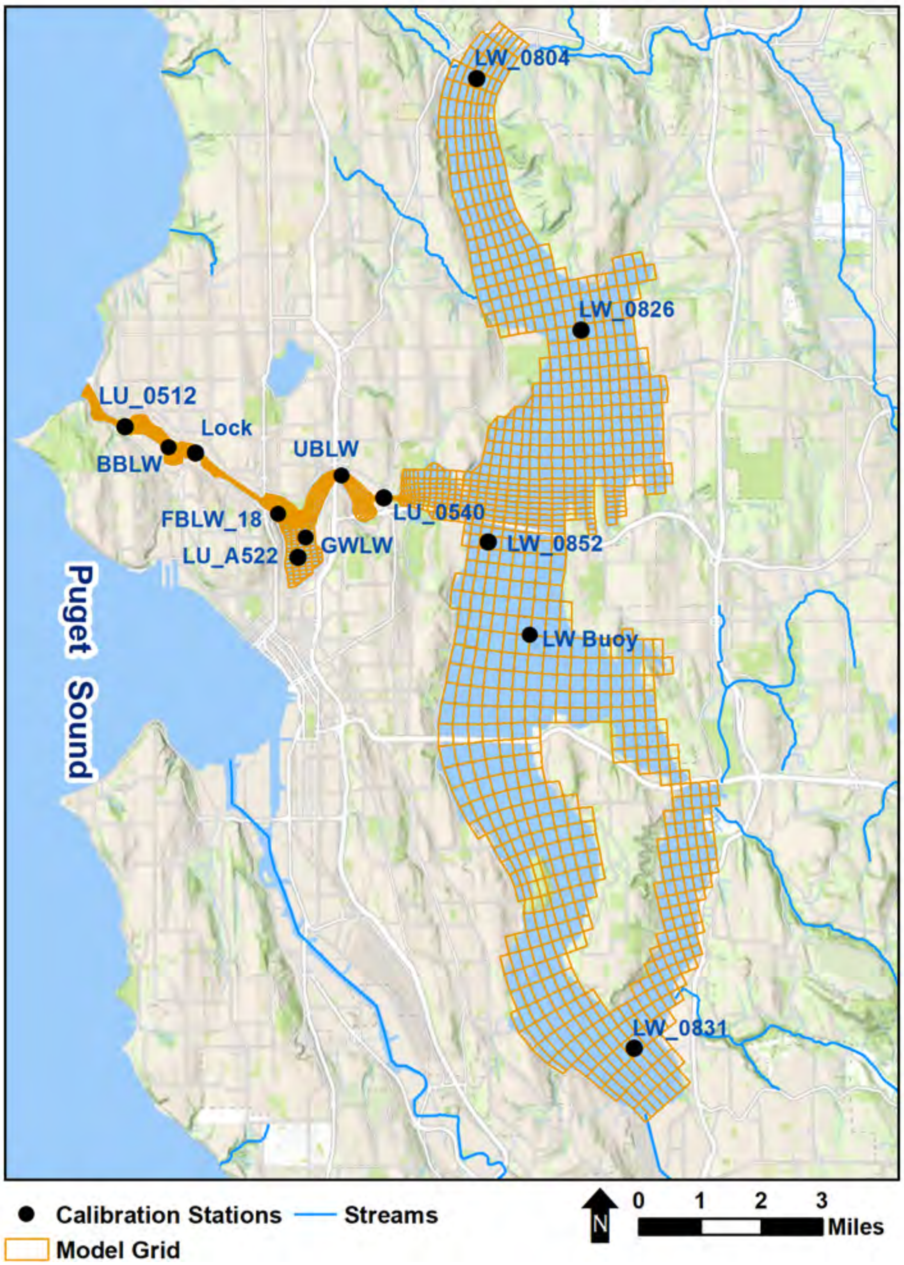

Figure D.1: The DSI Lake Washington Model extended grid, with currently available calibration locations.

Nghiem Tien Lam is DSI's Chief Engineer for this project. His role is to supervise and guide day-to-day tasks for the project.

Bui Minh Hoa is a Water Resources Engineer and DSI's lead modeler for the project.

Table D.1: Project Personnel and Role

Name	Role	Affiliation
Kester Scandrett	General Manager	DSI
Thomas Mathis	Technical Lead	DSI
Nghiem Tien Lam	Chief Engineer	DSI
Bui Minh Hoa	Modeller	DSI

D.2.2 Project Schedule

Table D.2 lists the key project tasks and schedules, and each one is described below.

Table D.2: Project Schedule

Task Number	Task Title	Duration
1	Quality Assurance Project Plan	2 weeks
2	Improve Model Calibration for Existing Conditions	3 weeks
3	Baseline LWSC Model Report	3 weeks
4	UW/SPU District Energy Scenario Model	3 weeks
5	Each Additional Scenario Model (Quantity TBD)	3 weeks
6	Report Finalization, Project Closure, and Next Steps	2 weeks
Sub-Total	Tasks 1-6: UW/SPU and One Additional Scenario Model	13 weeks

D.2.2.1 Quality Assurance Project Plan

The present appendix represents the deliverable for Task 1. The QAPP, which sets out the systematic planning process for this project, follows USEPA guidance and includes the key elements summarized in the Chapter 1 of this report (Introduction). These include a description of the project, goals, and objectives; project organization, responsible personnel, and schedule; data quality and model performance objectives; and other required information. Upon completion of the report to which this QAPP is an appendix, several of the original sections in the QAPP were adapted into the main body of the report, including sections regarding data compilation and the modeling approach for calibration and validation. The remaining sections of the QAPP are included in this appendix of the modeling report for completion.

The original DSI Lake Washington Model is an existing modeling product developed and documented to a large extent. The current study consists of refining and extending that model Model-data comparisons will be used to establish model performance. The following model outputs will be compared to data:

1. Water surface elevation;
2. Temperature; and
3. Salinity.

Model-data comparisons will be reported as time series plots and statistical performance measures. General qualitative assessments of model performance will be used based on performance statistics.

D.2.2.2 Improve Model Calibration for Existing Conditions

The potential for improving the LWSC Model calibration for temperature and salinity will largely depend on the availability of additional data from the LWSC for wind conditions (speed and direction) and meteorology (atmospheric pressure, air temperature, relative humidity, solar radiation, and cloud cover). Note that if such data is unavailable or of inadequate quality, this task will focus only on ensuring satisfactory performance based on the QAPP.

Model calibration for density stratification generally focuses on adjusting several model parameters to minimize the differences between the model predictions and observations. These parameters include coefficients for surface heat flux, light attenuation (e.g., water clarity), and turbulence closure. Many model parameters can be fixed based on literature values and professional judgment regarding the sensitivity of model outputs to variations in model parameters. The model parameters, reasonable ranges of parameter variation (based on literature and professional judgment), and the qualitative performance criteria for evaluation will be described in the QAPP.

D.2.2.3 Baseline LWSC Model Report

Following Tasks 1 and 2, the Baseline LWSC Model Report (*i.e.*, the current report to which this QAPP is appended) will be prepared, including the following elements:

- Final QAPP, reflecting comments from LLTK and other Stakeholders;
- Summary of available data, including an evaluation of data quality and availability;
- Summary of the model development, including grid, boundary conditions, initial conditions, and simulation period;

- Summary of the model calibration and validation for the baseline simulation period. This will likely include model-data comparisons (*i.e.*, time series plots, scatter plots, and statistical summaries) for temperature and salinity at each water quality monitoring station in the LWSC and Lake Union; and
- Summary of graphical and statistical outputs to be compared with the scenario(s) of interest.

Since the original DSI Lake Washington Model has already been developed and calibrated, and outputs have been reported, many of the Baseline LWSC Model Report elements have already been completed. This will allow the report to be completed more efficiently and allow more of the project budget to be directed toward evaluating scenario(s) of interest.

D.2.2.4 Three Additional Scenarios

The model scope includes three additional scenarios. Additional scenarios may include one or many outfall configurations, temperatures, and flows at discrete locations to be determined before any modeling. Comparisons of the scenario models to the Baseline LWSC Model will be performed based on the standard graphical and statistical outputs established in previous tasks.

Generally, we anticipate the details of additional scenario(s) to be established following Tasks 3 and 4. We also recognize that additional scenario(s) may be the subject of ongoing discussion and that one or several may ultimately be requested. In general, we anticipate that discussion regarding additional scenarios could begin two months after project kickoff and that additional scenarios could be conceptualized, developed, and analyzed within two weeks. To provide LLTK and stakeholders with maximum flexibility for requesting additional scenario(s), we have made several assumptions in formulating a general cost estimate for *à la carte* additional scenario(s):

- One 30-minute meeting to discuss ideas, and specifications of the requested scenario, including cold-water injection outfall location, flow rate, temperature, or other configuration parameters;
- Creation of the discussed model scenario, including the modification of model input files for boundary conditions or initial conditions as discussed in the initial meeting for a given scenario;
- Running and post-processing the model outputs to produce the standard graphical and statistical outputs from the Baseline LWSC Model Report and other scenarios; and
- Preparation for a one-hour project update meeting for LLTK and stakeholders to describe the scenario setup and share graphical and statistical comparisons with the Baseline LWSC Model and other previous scenarios. This deliverable will include any meeting slides, recordings, or meeting minutes.

D.2.2.5 Report Finalization, Project Closure, and Next Steps

A final report will be prepared to include final versions of the QAPP and Baseline LWSC Model Report and comprehensive documentation of all scenarios performed to ensure the project can be properly closed out. As all elements of this final report will have been developed before Task 6, this task reflects the level of effort necessary to compile documentation into a single coherent deliverable report, and we do not assume any additional analysis or report will be required. We assume that the draft final project report deliverable for this task will undergo one round of review and revision before being finalized.

Based on discussions from prior project update meetings and other discussions with LLTK and other stakeholders, this report may also include the next steps for future work to be performed.

D.3 Quality Objectives

Quality objectives are statements of the precision, bias, and lower reporting limits necessary to meet project objectives. Precision and bias together express data accuracy. Other considerations of quality objectives include representativeness, completeness, and comparability.

D.3.1 Data Quality Objectives

Data quality objectives are qualitative and quantitative statements that clarify the intended use of data, define the types of data needed to support a decision, identify the conditions under which the data should be collected, and specify tolerable limits on the probability of making a decision error because of uncertainty in the data.

Data of known and documented quality are essential to the success of any water quality modeling study, which will be used to generate information for decision-making. Model calibration will be accomplished using data available from various sources. All data used in this modeling effort will be reviewed for quality and consistency with other relevant data and for reasonableness in representing known conditions in the study area.

The QA/QC goals for this project are:

- Objectivity — all work should be based on a methodology and use a set of evaluation criteria that can be explicitly stated and applied.
- Thoroughness — All study elements should be documented thoroughly.
- Consistency — all work should be performed and documented consistently.

- Transparency — The documentation will clarify the data source used, the assumptions used in the modeling, and the results obtained.

D.3.2 Model Quality Objectives

USEPA, 2002 emphasizes a systematic planning process to determine the type and quality of output needed from modeling projects. This begins with a Modeling Needs and Requirements Analysis, which includes the following components:

- Assess the need(s) of the modeling project;
- Define the purpose and objectives of the model and the model output specifications; and
- Define the quality objectives to be associated with model outputs.

The first item (needs assessment) is covered in the description of the project (see Section D.1.1). Simulation models are needed to develop a scientifically robust and defensible LWSC model. The existing model framework, consisting of the Lake Washington model previously developed by DSI using the EFDC+ Explorer Modeling System, are sufficient to meet this purpose, and the creation of new models (*i.e.*, model code) will not be required.

The modeling study design (documented in the report to which this QAPP is appended) was developed to (1) represent the full range of physical processes that impact the distribution of temperature and salinity in the LWSC, and (2) address each of the following study objectives, which also serve as the data quality objectives for model output:

- Develop a technically defensible hydrodynamic model which simulates the existing conditions of temperature and salinity within the LWSC;
- Use calibrated and validated model results to determine the response of the LWSC to the proposed cold-water injection; and
- Develop a scientifically-sound model to determine the necessary cold-water input locations, volumes, and temperatures to meet (or come as close as possible) the stated temperature thresholds for migrating salmon habitat.

Determining whether the data quality objectives have been achieved is less straightforward for a modeling study than for a typical sampling and analysis study. The usual data quality indicators (e.g., completeness, accuracy, precision) are difficult to apply and often do not adequately characterize model output. Nevertheless, objective techniques can be used to evaluate the quality of model performance and output.

In general, the modeling effort must be designed to achieve an appropriate level of accuracy and certainty in achieving the principle study need. The primary modeling quality objective is to characterize the model's assumptions, limitations, adequacy of fit, and uncertainty. Natural resource managers, stakeholders, and policymakers can thereby evaluate the quality and uncertainty of model results against the magnitude of the potential decision or regulatory actions to determine which decisions the model results can support. Therefore, this study must provide a clear, accurate, and thorough job of communicating each aspect of the model.

E STATISTICAL CALCULATION METHODS

In the below mathematical notation, observations are denoted by O_i for individual measurements in space and time. P_i represents the corresponding model prediction in space and time as the observed value O_i. N represents the total pairs of observed and model-predicted values.

The mean of the observed value $\overline{O}$ is computed as:

$$\overline{O} = \frac{1}{N}\sum_{i=1}^{N} O_i$$

and the Mean Predicted value $\overline{P}$ is:

$$\overline{P} = \frac{1}{N}\sum_{i=1}^{N} P_i$$

To compute the standard deviations of the observed and predicted values, the following formula is used where X_i can be either the observed O or predicted P value:

$$\sigma_X = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^2}$$

Herein, the subscripts σ_{obs} and σ_{pred} will be used to denote the standard deviation of the observations and predictions, respectively.

The Mean Error (ME) is the difference between the average of the predicted and observed values:

$$ME = \overline{P} - \overline{O}$$

Where values of ME closer to zero indicate better model performance, note, however, that a large predicted variance, where large errors occur in the positive and negative direction relative to the observations, can effectively cancel out, producing a deceivingly small ME.

The Relative Mean Error (RME) is calculated as the mean error normalized by the observed mean, taken as a percentage:

$$RME = \frac{\overline{P} - \overline{O}}{\overline{O}} \times 100\%$$

The RME is a helpful complement to the ME but suffers from the same limitations. Additionally, if the observed mean is extremely small then even small mean errors can appear quite large, and conversely, could appear deceptively small if the mean error is small, but there are large positive or negative errors which tend to cancel out using the ME formula.

The Mean Absolute Error (MAE) provides a similar measure to the ME, with the exception that, by taking the absolute deviation between the observed and predicted value, large positive or negative errors contribute to the MAE in the same direction:

$$MAE = \frac{1}{N} \sum_{i=1}^{N} |P_i - O_i|$$

The MAE can, therefore, more accurately reflect differences between the observed and predicted values.

The Root Mean Square Error (RMSE) reflects the standard deviation of the differences between the observed and predicted values. The RMSE is computed as:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (P_i - O_i)^2}$$

Combined with the MAE, which quantifies the absolute error, the RMSE provides a quantification of the standard deviation of the errors.

The Relative Root Mean Square Error (RRMSE) is the ratio of the RMSE to the observed mean, taken as a percentage:

$$RRMSE = \frac{RMSE}{\overline{O}} \times 100\%$$

Similar to the RME, when the observed mean $\overline{O}$ is close to zero, the RRMSE can become unreasonably large. Therefore, when $\overline{O}$ is close to zero, the RRMSE is not recommended.

The Scaled Root Mean Square Error (SRMSE) is the RMSE normalized by the observed variance of the observations:

$$SRMSE = \frac{RMSE}{O_{max} - O_{min}} \times 100\%$$

The SRMSE is particularly useful for cases where the observed mean is close to zero, but a large range of variance is observed. In comparing stations where the range of a particular value, such as salinity or water surface elevation, can be large relative to the mean value and vary significantly from station to station, the SRMSE provides a valuable measure of model performance overall, keeping the errors in perspective relative to the overall range of the observations.

The Centered Root Mean Squared Error (CRMSE) relates three statistical measures: the correlation coefficient between the observed and predicted values (R), and the standard deviation of the observed σ_{obs} and predicted σ_{pred} values.

$$CRMSE = \sqrt{\sigma_{obs}^2 + \sigma_{pred}^2 - 2R\sigma_{obs}\sigma_{pred}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\left(P_i - \overline{P}\right) - \left(O_i - \overline{O}\right)\right]^2}$$

The Correlation Coefficient R is a statistical measurement of a relationship between two variables. The correlation coefficient value ranges from [-1, +1], and its absolute value closer to +1 indicates a strong positive linear correlation between the observed and predicted value.

$$R = \frac{\sum_{i=1}^{N}\left(O_i - \overline{O}\right) \times \left(P_i - \overline{P}\right)}{\sqrt{\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2 \times \sum_{i=1}^{N}\left(P_i - \overline{P}\right)^2}}$$

The coefficient of determination R^2 is the square of the Correlation Coefficient R and has a similar meaning. With both R and R^2, it can be observed that the ratio between the mean observed and predicted value is not explicitly considered. Rather, a high positive value for both statistics can be achieved if the mean observed and predicted values are effectively offset, thus having the same deviations relative to the respective mean values. Therefore, it is essential to evaluate the ME, RME, and MAE along with the R and R^2 values to ensure the model predictions are appropriately represented.

The Nash-Sutcliffe Index of Efficiency (NSE) varies from $-\infty$ to +1, with values close to 1 considered optimal. NSE values less than 0 indicate unsatisfactory model performance.

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(P_i - O_i\right)^2}{\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2}$$

In terms of the other statistics described thus far, the NSE can also be written as:

$$NSE = 1 - \frac{RMSE^2}{\sigma_{obs}^2}$$

Thus the NSE rewards models with a small standard deviation of errors relative to the standard deviation of the observations.

The Coefficient of Efficiency (COE) ranges from $-\infty$ to +1, with values closer to +1 indicating more optimal predicted values relative to the observations.

$$COE = 1 - \frac{\sum_{i=1}^{N} |P_i - O_i|}{\sum_{i=1}^{N} \left|O_i - \overline{O}\right|}$$

Similar to the NSE, the COE represents a ratio between the sum of the absolute errors and the sum of the absolute observed deviations. From this, we can observe that a COE close to +1 could not be obtained if the standard deviation of the observations is close to zero, even if the MAE is relatively small.

The Index of Agreement (IOA) is similar to the NSE and COE and can be written as:

$$IOA = 1 - \frac{\sum_{i=1}^{N} |P_i - O_i|}{\sum_{i=1}^{N} \left(\left|P_i - \overline{O}\right| + \left|O_i - \overline{O}\right|\right)}$$

As with the other statistics discussed which are normalized by the observed mean, if that value is close to zero then the IOA becomes the ratio of the sum of the absolute deviation and the sum of the observed and predicted value, making a value close to +1 for the IOA relatively trivial as the denominator is sure to be larger than the numerator. Therefore, for observed parameters where the observed mean value is close to zero, the IOA is not recommended.

The Kling-Gupta Efficiency (KGE) is a model evaluation criterion that can be decomposed into the contribution of the mean, variance, and correlation coefficient. KGE is similar to NSE, COE, and IOA in that it ranges from $-\infty$ to +1, and the closer to +1, generally the more accurate the model:

$$KGE = 1 - \sqrt{(R-1)^2 + \left(\frac{\overline{P}}{\overline{\overline{O}}} - 1\right)^2 + \left(\frac{\sigma_{pred}}{\sigma_{obs}} - 1\right)^2}$$

The KGE measures how well a hydrological or environmental model reproduces observed data in terms of three components: correlation, variability, and bias. The correlation component assesses how well the temporal patterns of observed and simulated data match. The variability component evaluates the similarity in the spread of data points between the observed and simulated data, and the bias component measures the difference in means between observed and simulated data. The formulation of the KGE ensures that the value will be a reliable measure of the relative accuracy and precision of the model, as well as the linearity of the predicted and observed values, combining statistics that are similarly defined and will generally be of similar orders of magnitude, and therefore not subject to limit issues as with the COE, for example.

F RESPONSES TO COMMENTS ON THE DRAFT MODEL RESULTS SUMMARIES FOR THE BASELINE AND SCENARIO MODELS

DSI presented results of the baseline and scenario simulations to stakeholders, and received two sets of comments: from Curtis DeGasperi as a representative of King County, and from Kent Easthouse as a representative for the U.S. Army Corps of Engineers.

We have provided the original text of these comments our and responses to them in the below sections.

F.1 Response to Comments Received from King County Representative Curtis DeGasperi on May 2, 2023

Comment 1: I already suggested that it might be easier to initialize the model on Jan. 1 and provide results on a calendar year. I don't expect that to improve the calibration, but perhaps something worth exploring If possible.

Response: We think this is a good idea and will revise the models to start on the calendar year. As you said, it will allow us to initialize the salinity conditions more accurately since that is the time when concentrations are generally close to zero.

Comment 2: There are some bad wind direction data evident in the plots for the buoy weather station. I think I mentioned previously that this would be an issue. They are the periods where wind direction does not change much and can be seen in data from each year. I'd suggest removing them from the input data. This is an issue that I've been trying to get our lab to resolve but have not had any success so far.

Response: Thank you for picking up on that. We will fill the wind time series with nearby data or alternatively switch off the LWBuoy wind forcing over that period to address the issue.

Comment 3: It looks like the Sammamish River inflow is based on data from Station 51T near Woodinville. However, I think I shared previously with DSI that this gage does not include the contributions of Little Bear, North, or Swamp creeks nor the Sammamish valley drainage downstream of the gage. I would suggest using a simple area-based scaling factor to better account for these ungaged flows. For a previous project it looks like I scaled May Creek daily flows to estimate these mostly ungaged inputs. It's also possible that DSI has scaled those flows but did not footnote that in the figure.

Response: Yes we recall that feedback on an earlier version of the model, and that surface flow should have been scaled to adjust for ungaged area as you suggest. We will double-check the model inputs to confirm.

Comment 4: It looks like the model consistently underpredicts water temperature at Station 0852 at 10-m depth from June-Sept. I suspect that the model does not resolve the summer thermocline accurately. This is a common problem with these models. Unfortunately, the means that the temperature of the water entering at Montlake is not accurately represented. The model suggests a gradient of temperatures over the surface 10 meters, but the data indicate that the surface 10 meters are generally pretty uniform.

Response: We provided a link for you to download the complete set of model-data vertical profile comparisons.

As you indicated, overall it can be very difficult to achieve excellent fit at all times between the model and data. We continue to work to improve the model and have several options to potentially address this issue. The principal component driving the depth of the surface mixed layer comes from momentum flux from the winds; moreover, the vertical profile at any point in a large, open body of water can also be a function of basin-scale seiches and internal waves. One potential solution or strategy to address this critical area of the model would be to adjust the 'weighting factor' of the wind stations nearby. For example, because of the proximity of the 0852 station to three wind stations (LW Buoy, WSEAT, and UW), the wind stress around this area is currently a function of the inverse distance of each cell from each of those stations, where each station is weighted equally. If we reduce the weighting of UW, or WSEAT, or conversely increase the weighting of LW Buoy, then we might see some deeper mixing in the surface layer around this location.

Comment 5: As Tom showed in the meeting, Gasworks temperatures are overpredicted at 36-ft (although there is a question regarding exactly what deep depth is represented by this station series). Salinity is also underpredicted at this location/depth. However, I'm not sure the temperature issue is related to the salinity prediction error (see next item). The prediction error may be related to the ability of the model to resolve the lake temperature gradient (similar to the issue at 0852).

Response: Thank you for this comment. There are a few factors to look at concerning the situation in Lake Union. The first is that the depth of the station needs to be accurately specified. I believe Kent Easthouse said it could be up to 7-10 lower in the water column, which could be pretty big. The second would be the salinity, for which a small change in concentration changes the density dramatically with respect to relatively large changes in temperature. The other factor is the variability of water quality and its subsequent impact on light attenuation (and thus temperature dynamics), which is an important source of uncertainty we must consider at this stage, specifically for Lake Union and LWSC stations. Based on our experience with other systems, most recently a model we have been working on for Lake Mendota in Wisconsin (a hyper-eutrophic lake), we see that changes in water quality can often lead to sudden shifts in temperature like we see in the data for Lake Union and Lake Washington but are not picked up by the model. Specifically, looking at the LW Buoy 15-m station, we see large jumps in temperature near the end of every summer. We see the same pattern in the LWSC at Freemont Bridge, most dramatically in 2019, when temperatures are increasing relatively slowly and show impacts of internal motion around a sharp thermocline, and then suddenly jump up where they are very close to the model predictions.

Comment 6: Tom also showed that temperature was also overpredicted at Fremont Bridge 40-ft depth. However, salinity was only overpredicted in 2019. This suggests to me that these temperature prediction errors are not just due to salinity prediction errors.

Response: Similar to the previous response, the interpretation of this station data indicates changes in temperature due partially to changes in salinity, and partially to changes in the optical properties of water as a function of changes in water quality. Since we are not currently considering water quality, we cannot capture changes in the optical properties of water, so they are held constant throughout the simulation. Although we heavily emphasize the role of salinity, that is only because we have not yet explored the interplay and feedback between temperature, salinity, and water quality.

To clarify our thinking on this, consider the components of the temperature continuity equation in the model (neglecting advection, diffusion, external sources and sinks and bed heat exchange for simplicity):

$$-\frac{\rho c_p A_b}{H}\frac{\partial T}{\partial z} = H_L + H_E + H_C \tag{F.1}$$

Here H_L is the heat flux due to longwave radiation at the surface, H_E is the latent heat flux at the surface, and H_C is the sensible heat flux at the surface. ρ and c_p are the water density and specific heat of water, respectively. H is the water depth, and $\partial T/\partial z$ is the change in temperature with respect to depth. A_b is the turbulent diffusivity between layers. Below the surface, all of the surface terms on the RHS are equal to zero, and $\partial T/\partial z$ becomes a function of the initial temperature conditions in each layer (which become smaller over time depending on the magnitude of A_b i.e., turbulent mixing due which arises due to a balance between shear and stratification), and shortwave radiation absorption.

As a function of this partitioning between the surface and interior water layers, there are only two components of the model that can be used to adjust the mixing depth: depth of stratification, and water temperature and depth, those being the attenuation length (considered constant in the current model, but can vary sharply due to changes in water quality) and the parameterization of turbulent mixing.

Due to this fact, we generally consider the temperature model calibrated when we see that surface temperatures are accurately predicted, and the deeper stations, which show little to no influence of solar radiation are appropriately predicated. As you noted, the temperatures around the thermocline are a bit more complicated. Usually, when we are aware of changes in water quality in the system, we tend to weigh those thermocline transitions a bit less until we have explored what introducing variable water quality might do to the light attenuation at different stations. To be clear, we can tune the mixing parameterization, to some extent, by adjusting the parameters of the turbulence closure model within a realistic range, but this is often less impactful than surface forcing data or changing the apparent optical properties of water.

Comment 7: Large Locks surface temperatures are overpredicted June-Sept.

Response: As with the comment below, I assume this refers to the 12-ft depth station (LLLW-D12). The model extraction location for that station is inappropriate and should be excluded for temperature and salinity at this point. That sonde location, as we understand it, refers to the temperature in the distribution well of the fish ladder. Conceptually, we understand that conditions at that location are a function of flow from the saltwater drain, the water stage downstream, and flow from the surface at the top of the fish ladder. Therefore, the data from this location is somewhat more difficult to interpret but does have some utility for understanding the function of the old saltwater drain, as indicated by the slides Eric Warner sent out.

Comment 8: There seems to be some issue with the salinity data/model comparison for the Large Lock at 12-ft depth. The observed salinities appear to be much greater than the salinities reported for the 32-ft depth which doesn't seem plausible. The 12-ft depth salinities look similar to the reported bottom salinities.

Response: Please see the response to the comment above.

Comment 9: I saw the error statistics reported for the King Co. routine monitoring at A522. I would like to see profile plots of temperature and salinity (model/data) compared for this station to see how the model resolves the observed gradients in these parameters. [Note: I saw some temperature profile comparisons for Lake Washington stations, but I wasn't sure which symbol (point or line) was the model or data. I suspected that the blue lines were the model output, but the plots would then seem to contradict the underprediction of temperature at 10-m depth.] An alternative would be to plot time series for temperature and salinity (simple conversion of our conductance data to salinity) for 1, 5, 10, 14-m depths at A522. I think Tom presented some of those plots, but I did not find them in the PowerPoint slides.

Response: The vertical profile outputs for all years and stations have been provided at the link in the response to comment #4 here. You are correct that the blue line represents model results. We will ensure that the legend is displayed in future outputs. Due to the quantity of data available for comparison, we tend to pare down some stations for brevity. For stations with more continuous profiles, sometimes we will just extract the temperature at a specific depth so that we can evaluate model performance relative to data from a few different perspectives.

F.2 Response to Comments Received from US Army Corps of Engineers Representative Kent Easthouse on June 30, 2023

Comment 1: I would recommend improving the temperature and salinity calibrations of the baseline model before continuing with the scenarios.

Response: We've been clear that the model calibration is a work in progress.

As far as the value of the scenario runs at this stage, the absolute temperatures at this stage are less important than the relative difference between the runs.

Comment 2: Where is station BBLW 2018 data?

Response: These data were not included in the FOIA request, so we are unsure if these data are available.

Comment 3: I am a bit uncertain of the error statistics being used. I am used to seeing the Mean Error (ME=1nTM-TO), Mean Absolute Error (MAE=1nTM-TO), and Relative Mean Square Error (RMSE=1nTM-TO2). Can they show the equations used to calculate the error statistics.

Response: We have updated the error statistics table in the report to include these statistics for salinity. Equations for all statistics provided are given in the QAPP.

Comment 4: I would suggest showing the error statistics for the June-Oct critical time period in addition to the entire year statistics.

Response: In the report, we have provided tabular summaries every month, relative to the critical habitat thresholds.

Comment 5: I would suggest re-checking the salinity error statistics (especially the mean error values) shown in the tables just to make sure they are accurate. For example, the error statistics shown for the LLLW-43 and GWLW-36 seem too small compared to the data shown on the graph.

Response: All error statistics have been re-computed and verified in the present report.

G RESPONSE TO COMMENTS RECEIVED ON THE DRAFT MODEL RESULTS REPORT, AUGUST 9, 2023 FROM LUCAS HALL (LONG LIVE THE KINGS) AND CURTIS DEGASPERI (KING COUNTY)

A number of questions and comments were received from Lucas Hall (Long Live the Kings) and Curtis DeGasperi (King County) on August 9, 2023. General comments and questions were provide in the body of an e-mail, while several editorial changes and clarifying points or questions were provided in the draft report PDF. All editorial changes recommended to the report were considered and accepted. Efforts were made to provide clarification and additional details where requested.

The remainder of the present section is devoted to responding to general questions and comments provided in the body of the e-mail, dated August 9, 2023 from Lucas Hall, which also provided detailed comments from Curtis DeGasperi.

G.1 Comments from Lucas Hall

Comment 1: For the Fremont bridge, why would scenario 2 appear as effective as 3 when 3 is discharging very close by? Is it just because the west diffuser on scenario 3 are just downstream of Fremont bridge?

Response: Scenario 2 uses a much larger flow at Montlake, and overall the total flow between scenarios 2 and 3 is similar. Taking the totality of the results, it appears that scenario 3 diffusers in Fremont Cut are interacting with the salt wedge, resulting in lower salinity levels farther upstream into the ship canal. By keeping salty water out of Lake union, the cold water from the Montlake Cut diffusers is more likely to settle into the bottom of Lake Union, than it is to float across the top of a salty layer, as we see in Scenario 2, where salinity still reaches Lake Union.

Comment 2: What's going on here and why doesn't is appear in baseline temperature?

Response: That is the bottom barrier called for in the conceptual drawings from Jacobs. It appears in all scenarios in the Montlake cut, but does not appear in the Baseline model, as it does not reflect current conditions.

Comment 3: The graphics in the report make it appear like the baseline calibration is poor for salinity, yet the narrative seems satisfied with the salinity calibration. The reasons that the report cites for the poor appearance of the salinity calibration (low salinity calibration, baseline data is limited, etc.) seem to point to how it is difficult to assess whether the modeling is calibrated well, not that it is adequately calibrated. Does the report overstate the salinity calibration?

Response: I understand your concern. At many stations, note that the overall observed salinity concentration is usually very low. When we zoom the Y-axis to show the range of data more clearly, you can get the impression that the calibration for salinity is poor. Looking quantitatively at the data and model results, however, shows that most stations show a model error of much less than 0.1 ppt. Generally, salinity concentrations at GW Park and Fremont Bridge don't exceed 5 ppt, Ballard Bridge stations concentrations vary between 0 and 10 ppt, and the Large Lock varies between 0 and 20 ppt. At each of these stations, understanding model differences relative to the overall concentration is generally more important, while RMSE, and other variance based measures of performance can tend to tell a pretty pessimistic story. Take for example Figure 7.61 showing the salinity comparisons between Baseline, Scenario 1B, and observations at the Large Lock 43' station. Generally we see that the model is tracking very well with observational trends, but the range of variations is quite a bit less in the model. This is something I have discussed before, but the sensors collect data at a much different spatial and temporal scale than the model cells we compare them too, so we don't expect to see all the variability in the model that we do in reality. That said, variance-based statistics are going to give the impression that the model performance is poor, because the range of variation is not captured well by the model. There are some approaches to try to overcome this issue that we can explore at later stages, such as applying smoothing to the observation and model result to remove some of these high frequency variations in the data and get it closer to what we would expect the average behavior of the model to track with.

Comment 4: The salinity calibration and model results are difficult to interpret. Could you provide more analysis around impacts to salinity expected from these scenarios?

Response: At the present stage, the primary impact we see is the potential for mitigation of saltwater intrusion into the ship canal. At appears in Scenario 3 that the addition of diffuser in Freemont Cut essentially stopped the salt wedge from propagating past Fremont Bridge and into Lake Union. This fundamental difference from Scenario 2 seems to have resulted in more fresh water settling into the bottom of Lake Union rather than floating out across saltier water in the Lake Union hypolimnion and continue downstream more efficiently, rather than diving down into the deeper waters of Lake Union, as we see in Scenario 3.

Comment 5: The dye tracer graphs are difficult to read and some narrative descriptions to interpret the graphs would be helpful.

Response: We will add more narrative description.

Comment 6: I think the conclusion about engineering are a bit outside of the scope of this report.

Response: That's fair and we can remove the input on that front. In general, I think the consensus from our end is that a six-foot diameter pipe running along the bottom of the ship canal is going not likely to be feasible for a variety of reasons. Not the least of which is safety for boaters, and protection of the infrastructure from unintended damage from the public.

G.2 Comments from Curtis DeGasperi:

Comment 7: The barrier/diffuser implementation is a bit confusing for me. In the scenario cross-section color contour figures there appears to be a location where the bottom is elevated (the barrier?) and in the Baseline image it is missing. There still seems to be an elevated bottom segment in all of these figures, but I don't know if that is natural or added. I'd be surprised if there was a natural sill out in the Union Bay navigation channel. Lucas' image below captures those unspecified elevated locations.

Response: In the scenarios, there is a bottom barrier applied at the upstream end of Montlake Cut, as called for in the designs by Jacobs. This does not appear in the baseline model.

Comment 8: Intro page 1-1 Lake Washington dropped an average of 9 (not 6 feet) as a result of the Lake Washington Ship Canal project....Lake Washington was lowered to the mean elevation of Lake Union.

Response: We will revise this statement for accuracy.

Comment 9: Intro page 1-1 "Key obstacles to salmon recovery in this watershed include...." This statement seems pretty strong given that this is probably more a belief than supported by any data analysis or modeling. Perhaps this could be stated something like "...are hypothesized to be key obstacles to salmon recovery."?

Response: We will revise this statement in the report.

Comment 10: Intro page 1-1 "The study discussed in this report aims to evaluate the hypothesis that cold water supplementation to the LWSC can improve water quality for the benefit of salmon." This seems to claim more than this modeling work can deliver. The model simply demonstrates how the system temperature will respond to technical engineering scenarios. The effect on salmon would require another type of model or data analysis. We know that adding cold water will make the system cooler, but the question the model answers is where, when, and how much.

Response: We will revise this statement in the report.

Comment 11: With respect to error statistics, it seems odd that Table 4.2 provides generalized guidelines (realize these are somewhat arbitrary) for model error/skill metrics, but only one of these metrics (NSE) appears in Table 6.8. There is a paper that summarizes model error statistics for many published models, including R2 and RE [note that Table 6.8 has a negative RE for temperature which is inconsistent with the RE formula in the report). The EFDC temperature model RE is in the 20th to 10th percentile of the models compiled by Arhonditsis and Brett, 2004 The EFDC overall RMSE for temperature 1.766 C would not be considered good by Ecology based on their modeling experience. None of the model error stats for salinity in Table 6.8 have a corresponding metric in Table 4.2 so it is not possible to make any statements based on these error stats. Unfortunately, Arhonditsis and Brett didn't summarize salinity error stats. Regardless, it does seem like the salinity errors are often quite large...seconding Lucas' comment below.

Response: Please see the response to a similar comment above. In general the magnitude overall and range of variation can play into how these statistics reflect the model performance. One key thing to keep in mind here is that this synoptic study by Arhonditsis and Brett, 2004 is that they explicitly reviewed biogeochemical/water quality models. We have said all along that a key feedback between water quality and temperature dynamics in the lake is not captured in our model, and we believe addition of it will have significant positive effects on the temperature predictions in the model. In general, based on my experience doing salinity modeling in tidal estuaries (not a perfect analogy, but perhaps the best you can expect given how unique LWSC is) it is usually very difficult to nail salinity concentrations when they are so small (less than 5 ppt). To help frame this in more relative terms, please have a look at the paper attached, which was presented by the USACE consultant, WEST, prepared in collaboration with Kent Easthouse (Rinehimer et al., 2019). First, note that their methodology for parameterizing the lock was substantially more simplistic that our model. This USACE study used a simple lock exchange approach, and as such had far more direct control on the amount of salinity present in the model at the upstream end of the large lock, whereas our model parameterized the action of the large lock explicitly based on recorded lockage events. Second, please compare their model performance statistics for temperature and salinity to ours, and you will see they are comparable, if not better in most cases. Again, not saying we don't want to do better, but if we are going to set the bar, I think this is a more appropriate benchmark.

Here is the table from the USACE study done by WEST Consultants:

Table 1. Model temperature and salinity errors for bottom stations from June - October 2014 for exchange coefficients (C_e) 0.40, 0.43 and 0.45.

		Mean Error			RMS Error		
	Location	C_e=0.40	C_e=0.43	C_e=0.45	C_e=0.40	C_e=0.43	C_e=0.45
Temperature	LLLW	-0.75	-0.85	-0.91	1.28	1.32	1.36
	BBLW	-1.05	-0.93	-0.88	1.52	1.41	1.38
	FBLW	-0.42	-0.18	-0.06	0.97	0.94	0.93
	GWLW	-0.27	-0.13	-0.02	0.99	1.07	1.12
	UBLW	-2.10	-2.16	-2.17	2.77	2.87	2.92
Salinity	LLLW	0.44	0.96	1.30	4.30	4.37	4.45
	BBLW	-0.49	-0.04	0.25	1.78	1.67	1.67
	FBLW	-0.84	-0.35	-0.02	1.29	0.94	0.82
	GWLW	-1.68	-1.21	-0.89	1.96	1.51	1.23
	UBLW	0.03	0.28	0.48	0.34	0.47	0.67

Figure G.1: Table showing model-data RMSE values for the study by Rinehimer et al., 2019.

Here are the analogous tables from our baseline model: Temperature – [8]

Keep in mind too, that the statistics provided by the USACE seem to have been aggregated over depth in some manner, but regardless, I think it is clear that our model certainly is within the range of model performance that the Corp generally considers to be acceptable for this system, given the inherent complexities.

Comment 11: Key Findings page 8-4 "This ultimately contributes to the mortality…" This statement seems speculative to me and perhaps is beyond what the modeling work can tell us.

Response: We will revise the statement to be more conservative.

Comment 12: I wonder if it might be possible to add lines showing the locations of the diffusers in the cross-section plots?

Response: We can add this to the plot.

[8] see model results presented in Section 6.1.3.2 and Appendix B.

Comment 13: For reference, the earlier Lake Washington 3-D model developed by the Corps (Cerco, Noel, and Kim, 2004) also provides a point of reference for temperature modeling errors:

Table 7-2 (Concluded)

Station	Constituent	Relative Error	Mean Error	Correlation	Variance
Station 852	Ortho-Phosphate (mg/L)	0.306	-0.00308	0.67	0.00004
Lake Washington Stations		0.197	-0.00167	0.69	0.00003
Lake Union Stations		0.326	0.00246	0.33	0.00008
826, 859, 890 (Apr-Oct) Level 1-6		0.374	-0.00311	0.66	0.00004
826, 859, 890 (Apr-Oct) Level 7-13		0.466	-0.00452	0.62	0.00004
826, 859, 890 (Apr-Oct) Level 14-41		0.331	-0.00455	0.43	0.00005
Station 852	Temperature (Celcius)	0.071	-0.80	0.97	1.23
Lake Washington Stations		0.089	-1.09	0.96	1.70
Lake Union Stations		0.034	-0.49	0.99	0.97
Surface < 10m		0.094	-1.13	0.96	1.63
Thermocline		0.111	-1.22	0.93	1.73
Deep Water > 20m		0.116	-0.94	0.93	0.64
Station 852	Total Nitrogen (mg/L)	0.097	0.03513	0.69	0.00339
Lake Washington Stations		0.071	0.02528	0.63	0.00705
Lake Union Stations		0.153	0.05272	0.68	0.00435
826, 859, 890 (Apr-Oct) Level 1-6		0.061	0.02168	0.72	0.00391
826, 859, 890 (Apr-Oct) Level 7-13		0.077	0.02912	0.64	0.00318
826, 859, 890 (Apr-Oct) Level 14-41		0.101	0.04085	0.26	0.00303
Station 852	Total Phosphorus (mg/L)	0.044	0.00087	0.49	0.00012
Lake Washington Stations		0.164	0.00345	0.35	0.00018
Lake Union Stations		0.398	0.00842	0.28	0.0001
826, 859, 890 (Apr-Oct) Level 1-6		0.051	0.00097	0.40	0.00013
826, 859, 890 (Apr-Oct) Level 7-13		0.050	-0.001	0.45	0.00012
826, 859, 890 (Apr-Oct) Level 14-41		0.069	-0.00161	0.41	0.00014

Temperature. Overall, computed temperature exceeds observed by roughly 1 °C. The excess is a little larger at the surface and in the thermocline than in deep water. The scatterplot (Figure 7-49) indicates the largest excess temperatures occur when observed temperatures exceed 10 °C. Relative error in temperature computations is less than 9 percent.

Chlorophyll. Overall, observed chlorophyll exceeds computed by less than 0.2 mg m^{-3}. Insufficient data exist to examine performance as a function of depth. The scatterplot (Figure 7-50) indicates that magnitude of computed error increases as a function of magnitude of observed chlorophyll. Similar behavior has been demonstrated in multiple alternate model applications. Relative error in chlorophyll computations is ≈5 percent.

Nitrogen. Observed total nitrogen exceeds computed by 0.025 g m^{-3}, on average. The computed shortfall in deep water is nearly double the shortfall at the surface. Computed nitrate is 0.022 g m^{-3} less than observed, on average, with larger discrepancies in the deep waters. Effectively, the entire deficit in total nitrogen is in the nitrate fraction. Observed ammonium exceeds computed by 0.0006 g m^{-3}, on average. Consistent with the other components, mean error is greater in deep waters. Relative errors for total nitrogen, nitrate, and ammonium are 7 percent, 12 percent, and 3 percent, respectively. Scatterplots (Figures 7-51

7-12 Chapter 7 Observation-based Calibration

Figure G.2: Table extracted from Cerco, Noel, and Kim, 2004

Response: As stated before, this is not such an apples to apples comparison here, as the study you are referencing included a full water quality eutrophication model, which allows for dynamic feedback between light attenuation and temperature dynamics. A more appropriate comparison at this stage, we believe, is the 2019 USACE study of the LWSC. Also, stations in the table above appear to have been aggregated in some manner, and the mean errors and variances are still greater than 1 degree in some cases. Comparing these statistics to our model, my overall impression is that the models compare reasonably well, and the deficiencies in our model can be well understood by the lack of water quality feedback, which we intend to add in future phases of work.

H RESPONSE TO COMMENTS RECEIVED ON THE DRAFT MODEL RESULTS REPORT, AUGUST 18, 2023 FROM KYLE WINSLOW, JACOBS

Sub-Comment 1: The calibration indicates modeled temperatures at depth well below measured temperatures at some locations, primarily at the Fremont Bridge and Gas Works sites. Modeled temperatures match measured values better at the east and west ends of the LWSC than in the center (relatively poorer performance at Fremont Bridge and Gas Works than at Ballard Bridge and University Bridge). This may indicate the model has more difficulty modeling temperature in Lake Union than in the narrower sections of the LWSC. The time series of temperature, particularly in the spring/early summer months (see Figure 7.19 as the primary example) indicate the model is missing some process affecting temperature near the bottom in Lake Union. The model performance is better at the surface, so perhaps the model isn't mixing temperature down into the water column enough. This is significant because if we are adding cold water and quantifying benefits, these benefits would be overestimated if we are not mixing enough in the deeper parts of the LWSC. If the model had more mixing and thus was able to reproduce measured near bottom temperature better, then the benefits of the project (temperature reductions with the water transfer) would likely look smaller.

Response: The baseline model performance has been improved to better account for the depth of the epilimnion, and the temperature around the withdrawal location. The model results from the different sides of Lake Union are interesting. On the south side of Lake Union, the model seems to capture the variations in the temperature far better than at Gas Works Park, or the deeper Fremont Bridge stations. We can speculate on the reason for these interesting differences: (1) inaccurate depth of sondes; (2) variations in water column light attenuation seasonally, which would not have been accounted for by the present model; or (3) other potential issues we have yet to understand conceptually.

Sub-Comment 2: A close review of tabulated results shows some inconsistencies with the figures in the report. For example, Table 7.6 and Figure 7.13 (August-September 2020 temperature at Gas Works for Baseline and Scenario 3) don't match. The Table says 60% of the Scenario 3 August and 99% of the Scenario 3 results for 2020 exceed the 16 C limit, but Figure 7.13 appears to show zero exceedances of 16 C during these two months.

Response: The statistical comparison tables have been updated and checked, regarding this comment as well as during the updated process.

Sub-Comment 3: Statistics showing reductions in temperatures from the project alternatives relative to modeled baseline temperatures are based on absolute modeled temperatures and do not account for the baseline being at times significantly below measured temperatures in the deeper portions of the system. Tables showing significant reductions in the percentage of days per month above a given temperature can be misleading if the baseline is just above the critical temperature, but the baseline is significantly lower than the measured data. Figure 7.15 (Fremont Bridge 2020) provides an example of this, where the stats showing the benefit of the water transfer can be misleading (Table 7.9 September).

Response: These comments are appropriate at the current stage. The updated model results, given the improved baseline model performance, should be more relevant to the absolute temperature thresholds. In cases where the model diverges significantly from the observations, it is critical to then consider the relative change between the baseline model and the scenario to get a glimpse of what the potential impact could by at that location. We expect model calibration and fine-tuning of the model to be an ongoing topic of discussion.

Sub-Comment 4: Water clarity could play a role in the accuracy of the modeled temperatures. If water clarity is distinctly different in Lake Union than in the narrow portions of the LWSC, the thermal regime could be conceivably different than that modeled with a uniform water clarity. However, I question whether this would have a significant impact on temperatures 30 to 40 feet below the water surface. Low water clarity would be more likely to increase water temperature at the surface as light transmission is reduced. Errors in Baseline temperature at Fremont Bridge are highest in May and June, which is likely before the nutrient/algal cycle would have the largest impact on local temperature.[9]

Response: The deepest stations at Gas Works Park and Fremont Bridge specifically show a pattern of temperature that is indicative of water quality-related variations in water clarity. Notably, we can see from the detailed statistics for the updated model in Appendix B that the largest deviations from the observations can be seen in the deepest stations at Fremont Bridge and Gas Works Park in the LWSC, and the 40 m and 50 m temperature at LW Buoy, and further that these deviations are in the opposite direction. In Lake Washington, the model begins to under-predict temperatures starting between 10 and 20 meters depth. In LWSC, the opposite is observed at Fremont Bridge and Gas Works Park stations, where the stations below 11 meters deviate from observations due to the model over-predicting the temperature at these depths. We believe this can be best understood by accounting for the differences in water quality processes, spatial scales, and drivers of mixing across this diverse waterway. We believe the model is already a significant step towards a comprehensive modeling approach for this dynamic range of processes.

[9] Copies of previous figures were omitted from the response for clarity considering the updated model results presented prior, and overall brevity.