Osoyoos Lake Climate Change Vulnerability Study

Phase 2 Study

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EXECUTIVE SUMMARY

The International Osoyoos Lake Board of Control has undertaken a multi-phase project to assess the vulnerability of Osoyoos Lake to a projected shift in climate. Operations of Osoyoos Lake, which is located at the border of British Columbia and Washington, are influenced by both the upstream Okanagan River and downstream Similkameen River. The availability of water in both basins influences how the lake is operated. Additionally, during periods of high flow, the Similkameen River can backwater or backflow Osoyoos Lake, controlling high water levels.

To support an analysis of Osoyoos Lake to a projected shift in climate, NHC previously developed hydrologic models of both the Similkameen and Okanagan basins (Phase 1). In the current study (Phase 2) the hydrologic models were integrated with the representation of Osoyoos Lake updated to better reflect current operating conditions. A hydraulic model of Osoyoos Lake and the Okanogan and Similkameen confluence has also been developed to support the understanding of backflow and backwater conditions. For the purpose of climate change simulations, backflow and backwater conditions have ultimately been represented within the hydrologic model using a multilinear regression. The hydrologic models were forced using five global climate models under two different emission scenarios.

Climate change is projected to change the hydrologic response of both the Similkameen and Okanagan basins, ultimately resulting in changes to Osoyoos Lake. In both basins, the freshet response is expected to shift earlier due to warming with lower freshet peaks because of less precipitation falling as snow during the winter months. Flows during the summer months are expected to decrease compared to historical conditions but increase in the fall and winter due to increased rainfall.

The shift in hydrologic response results in an increase in the frequency of Drought Condition 8a and Drought Condition 8bi (Similkameen and Okanagan freshet volume) being met. The frequency that Drought Condition 8bii (Okanagan Lake levels) is met is expected to decrease because of a disconnect between current Okanagan Lake operations and changes to future inflows. The combined effect on the overall drought conditions for Osoyoos Lake is an increase from present day. However, the only statistically significant increase occurs at the end-of-century (2071-2100) under SSP5-8.5 when the uncertainty in climate projections is the largest.

The number of times the upper lake level rule curve for Osoyoos Lake is exceeded is expected to decrease in the future, as a result of lower freshet peaks on the Similkameen. The frequency in which lake levels drop below the lower limit of the rule curve is expected to increase slightly in the future with the duration and magnitude of the events increasing. The limited occurrence of these events is in part due to a trade off between instream flow requirements and minimum lake levels, with lake levels taking precedence.

The analysis highlighted the dependence of Osoyoos Lake operations and levels on Okanagan Lake operations. In particular, the use of Okanagan Lake levels as a drought condition present challenges under projected climate change as it is influenced by changes to Okanagan Lake inflows and potential future changes to Okanagan Lake operations.

Building on this study, there are several steps that the International Osoyoos Lake Board of Control can take to further support the understanding of climate change vulnerability and guidance on future operations and Orders for Osoyoos Lake. This includes coordinating with studies that explore future operations on Okanagan Lake to understand how changes to Okanagan Lake operation will impact the operation and Orders for Osoyoos Lake. Additional analysis can also be undertaken using the current model to better understand the trade off between meeting minimum lake levels and instream flow requirements.

TABLE OF CONTENTS

TABLES AND FIGURES IN TEXT

TABLES

FIGURES

APPENDIX SECTIONS

APPENDICES

1 INTRODUCTION

The International Osoyoos Lake Board of Control (IOLBC) is conducting a multi-year, multi-phase project to assess the vulnerability of Osoyoos Lake to a projected shift in climate.

In 2021, NHC completed Phase 1 of the project that involved development of the Similkameen basin hydrologic model to partially assess the function of the International Joint Commission (IJC) Orders of Approval for Osoyoos Lake under projected climate change (NHC, 2021). Phase 2 of the project (this study) integrates results from the Similkameen modelling from Phase 1 with hydrologic and hydraulic modelling of the Okanagan ('Okanogan' in USA) basin to fully assess the Orders of Approval for Osoyoos Lake under climate change.

The scope of the current study (Phase 2) includes:

- Downscaling new climate change scenarios that cover a broader range of emission scenarios than those used in Phase 1.
- Updating and developing hydrologic and hydraulic models of Osoyoos Lake to simulate lake levels for the historic and future periods.
- Assessing how a changing climate impacts the current IJC Orders of Approval, particularly concerning lake level regulation.

1.1 Assumptions and Limitations

The following limitations and assumptions of this study should be recognized when interpreting the results and conclusions from this study:

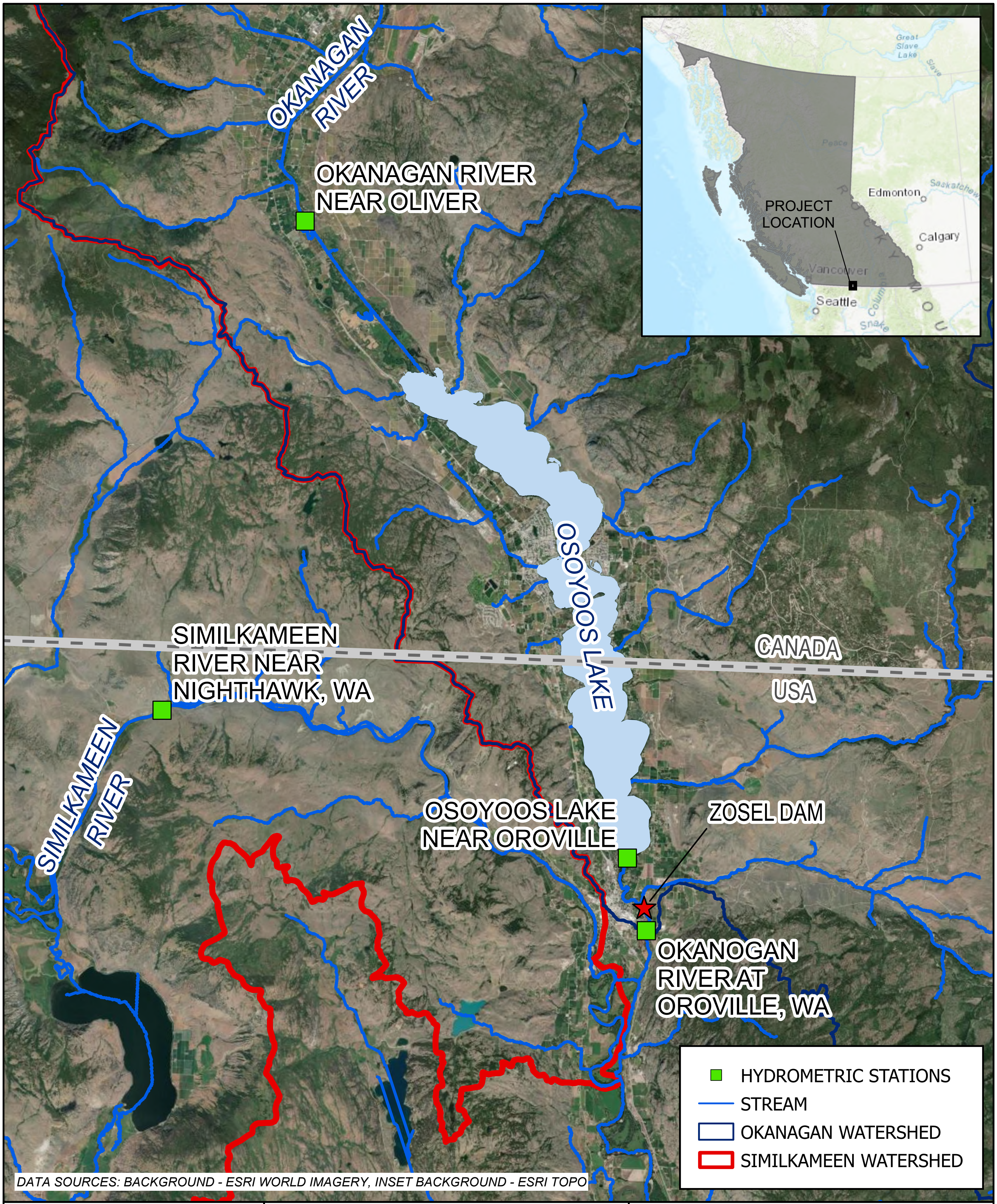
- Operations of the Okanagan mainstem lakes are based on idealized operations from the recent historic period and are assumed to stay consistent through the end of century. In reality, operation of the mainstem lakes include subjectivity due to the nature of manual operations. Operations of the lakes may change in the future. Notably, changes to the operations of Okanagan Lake will impact both the drought conditions and inflow hydrographs to Osoyoos Lake changing results from this study.
- The modelling of lake levels uses a simplified approach for modelling backwater and backflow effects. While the approach is appropriate for answering the questions within this study (number of times the upper rule is exceeded), the results may not be appropriate to assess the specific magnitude of lake levels such as in flood frequency analysis.
- Any projections of climate change are subject to substantial uncertainty, including:
    - Unknown future global greenhouse gas emissions
    - Uncertain global climate system response to increasing greenhouse gas concentrations
    - Incomplete understanding of regional outcomes from global changes

  - Complex precipitation processes that are difficult to simulate accurately in climate models
- The hydrologic models used in this analysis are conceptual and include an output that simplifies complex systems. Its construction is based on theoretical principals and assumptions that do not necessarily capture realistic nuances and complexity at a specific location.
- The hydrologic models do not take into account potential future land use and land cover changes within the watershed (e.g. increased population or major forest disturbance). Any future changes in land use and land cover require reassessment and potential redevelopment and calibration of the models. Future iterations of this work could incorporate these projections.
- The hydraulic model provided as part of this study is documented in Appendix A, and is subject to additional assumptions and limitations noted therein.

2 BACKGROUND

Osoyoos Lake spans the border of British Columbia and Washington, with the international border bisecting the lake (Figure 2.1). The Okanagan River, draining an area of approximately 7,550 km^2 (2,915 mi^2), flows into Osoyoos Lake. The Okanagan River upstream of Osoyoos Lake is highly regulated with multiple reservoirs upstream to maintain storage and flow needs within the Okanagan basin, which influences inflow to Osoyoos Lake. Downstream of Osoyoos Lake, the Okanagan River becomes the Okanogan River, which is joined by the Similkameen River approximately 2 km (1.2 mi) downstream of Osoyoos Lake. The Similkameen River, with a drainage area of 9,270 km^2 (3,579 mi^2) can contribute most of the summer baseflow to the Okanogan River downstream of Driscoll Island in summer months and cause backwater and backflow conditions in the Okanogan River upstream of Driscoll Island primarily during the freshet season.

The regulation of the trans-boundary lake is important for both countries to help prevent shoreline flooding on the lake and for maintaining downstream discharge on the Okanogan River for migrating, spawning and rearing fish. Zosel Dam, located 2.7 km (1.7 mi) downstream of Osoyoos Lake, was constructed in 1987 to maintain Osoyoos Lake water levels, replacing the original dam constructed in 1927.



DATA SOURCES: BACKGROUND - ESRI WORLD IMAGERY, INSET BACKGROUND - ESRI TOPO

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OSOYOOS LK CLIMATE CHANGE VULNERABILITY PROJECT OVERVIEW MAP

FIGURE 2.1

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The IJC Orders of Approval stipulate how water levels of Osoyoos Lake shall be managed (IJC, 2013) under non-drought and drought conditions. Under non-drought conditions, the Orders establish minimum and maximum elevations that Osoyoos Lake should be maintained within, to the extent possible (Figure 2.2). Under drought conditions, the allowable maximum and minimum elevations are adjusted, expanding the operating range and providing flexibility to store more water in the lake when needed or to accommodate lower levels when water supply is limited.

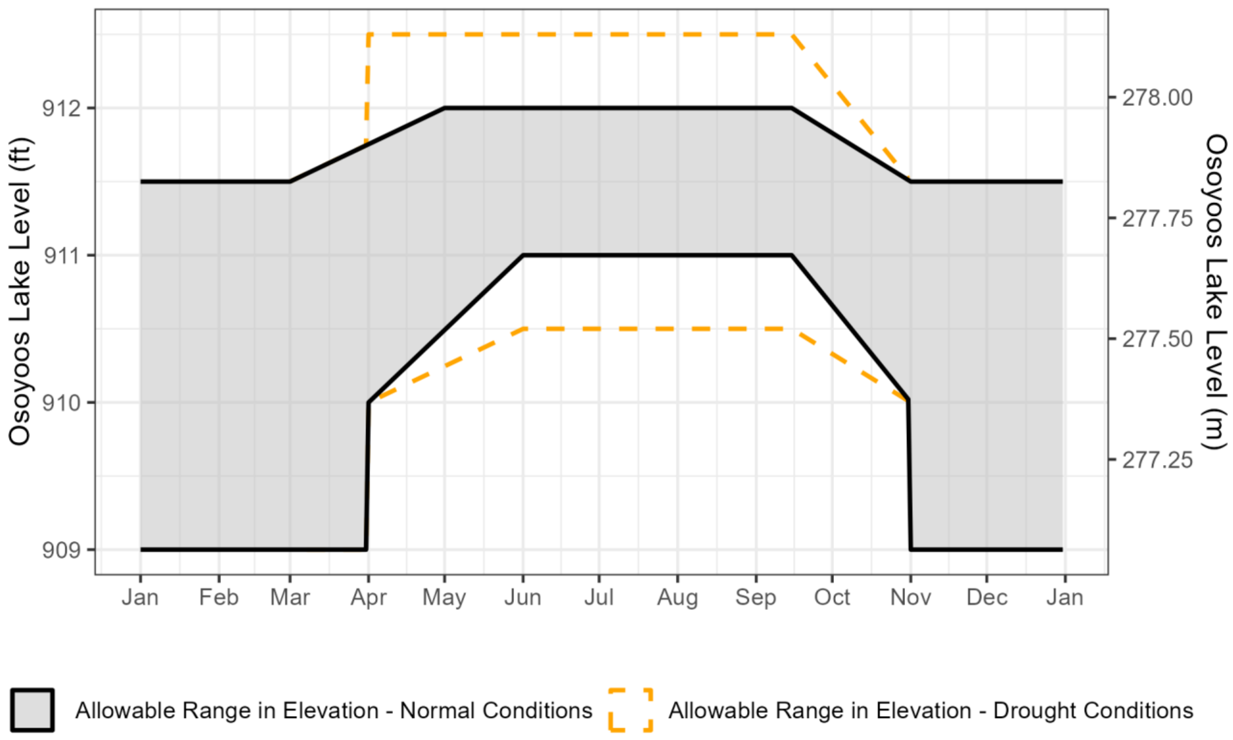

Figure 2.2 IJC Orders of Approval for Osoyoos Lake Levels

Drought conditions for Osoyoos Lake are defined by conditions on the Similkameen River and at Okanagan Lake using the following criteria:

- **Condition 8a**: The volume of flow in the Similkameen River at Nighthawk, Washington for the period of April through July as calculated or forecasted by United States authorities is less than 1.0 million acre-feet and
- **Condition 8b:**
  - i) The net inflow to Okanagan Lake for the period April through July as calculated or forecasted by Canadian authorities is less than 195,000 acre-feet or
  - ii) The level of Okanagan Lake fails to or is forecasted by Canadian authorities to fail to reach 1122.6 ft during June or July.

The level of Osoyoos Lake depends on the balance of inflow and outflow from the lake. Inflows to Osoyoos Lake are regulated by the outflow from Okanagan Lake. When flow on the Similkameen River is less than 10,000 ft^3/s (283 m^3/s), outflow from the lake is controlled by Zosel Dam. When Similkameen River flows exceed 10,000 ft^3/s (283 m^3/s), the Similkameen River backwaters Osoyoos Lake, constraining the outflow from the Lake. In extreme cases, when the Similkameen River flows exceed 20,000 ft^3/s (566 m^3/s), the river backflows into Osoyoos Lake. These threshold conditions are approximate and may vary depending on concurrent Okanogan River flow.

3 METHODS

To simulate the impacts of climate change to Osoyoos Lake, existing hydrologic models of the Similkameen and Okanagan basins were coupled. The Similkameen hydrologic model was developed in Phase 1 of the project (NHC, 2021) while the Okanagan hydrologic model was developed through an Okanagan Basin Water Board (OBWB) floodplain study with updates to support better handling of low flow conditions (NHC, 2020, 2023). Updates were made to the representation of Osoyoos Lake in the Okanagan model as part of this study to better simulate lake levels, as described in Section 3.1.

The two hydrologic models were driven by downscaled global climate model forcing data to produce long term simulations of Osoyoos Lake levels (Section 3.2).

3.1 Simulation of Osoyoos Lake Levels

Osoyoos Lake levels are influenced by inflows, the operation of Zosel Dam, and backwater or backflow from the Similkameen River. Operations of Osoyoos Lake have changed from the initial construction of Zosel Dam to present day due to upgrades of the dam, and changes to regulations and priorities, with some subjectivity inherent in human decision making. Replicating historical operations was not feasible and simplification was necessary. NHC consulted the IOLBC and the Washington Department of Ecology to simplify operations of the lake to represent idealized operations. For simulating lake levels, the model assumes consistent operation from the historical period through to the end-of-century, even though operations have changed with time and may change in the future.

The following section provides an overview of the representation of Osoyoos Lake in the Raven hydrological modelling framework, idealized operations of the lake, and how outflow from the lake was handled under normal outflow conditions and backwater or backflow conditions from the Similkameen River.

3.1.1 Hydrologic Model

The hydrologic model for the current study was developed by building upon and integrating two existing models: the Okanagan mainstem model and the Similkameen Basin model. The Okanagan mainstem model formed the core framework, while the Similkameen Basin model's output was incorporated into the new model through a simplified subbasin, ensuring seamless integration of hydrologic inputs.

The Okanagan mainstem hydrologic model, that includes Osoyoos Lake, was developed in the Raven hydrological modelling framework. In 2020, NHC developed the first Raven model of the Okanagan mainstem lakes for the OBWB floodplain mapping study with the primary focus of simulating peak lake levels and discharges. In 2023, NHC updated the Okanagan mainstem hydrologic model to better handle moderate and low flow, using the latest version of Raven at that time (v3.5).

For this study, NHC built on the updated Okanagan mainstem model from 2023. To leverage the latest reservoir handling capabilities, NHC updated the development version of Raven (v4.0, dated December 19, 2024) to handle outflows from Osoyoos Lake under various hydraulic conditions (e.g., backwater and backflow). The official release of this version is anticipated in early 2025. Updating the handling of reservoir operations on all the mainstem lakes to the development version was beyond the current study's scope. As a result, the model was split in two: the original version was used for simulating conditions upstream of the Okanagan River near Oliver gauge, while the development version of Raven (v4.0) was used from the Okanagan River at Oliver gauge to downstream of Osoyoos Lake. The Similkameen basin model was kept as a separate hydrologic model from the Okanagan model and is coupled with the Okanagan model as a flow input.

Within Raven, Osoyoos Lake was represented as a reservoir with a stage-storage-area curve. This curve was updated from previous versions based on new bathymetry data collected for Osoyoos Lake in 2021. The outflow from Osoyoos Lake was controlled at Zosel Dam and modelled through a series of rating curves, which were developed to relate flow releases from Zosel Dam to various contributing factors, including Osoyoos Lake levels and Similkameen River flows depending on the prevailing hydraulic conditions in the channel. Additional details on the representation of outflow from the lake are summarized in Section 3.1.3.

The operation of the lake was handled through an optimization problem of a series of user-defined management goals. Management goals can be used to define objectives like minimum or maximum lake levels or minimum downstream outflows. Multiple objectives can be weighted to prioritize one over the other. The optimization to the user defined goals is limited by the mass balance of the reservoir and any constraints which *must* be satisfied (not optional). Details on the idealized operation of Osoyoos Lake are described in Section 3.1.2.

3.1.2 Operation Goals of Osoyoos Lake

The operations of Osoyoos Lake are dependent on drought conditions as defined by the Similkameen River and Okanagan Lake. To allow for the variation in management of Osoyoos Lake between drought and non-drought conditions, the Similkameen model and Okanagan model upstream of Osoyoos Lake were run first in what can be considered a "forecast mode" to determine when drought conditions occur. Based on the results from this forecast, maximum, minimum, and target lake levels were set and the model portion including Osoyoos Lake was run.

Figure 3.1 summarizes the maximum, minimum and target lake levels used in the model simulations under both drought and non-drought conditions. Maximum and minimum lake levels are defined by the Orders of Approval while target lake levels were determined through discussions with the Department of Ecology based on recent operations.

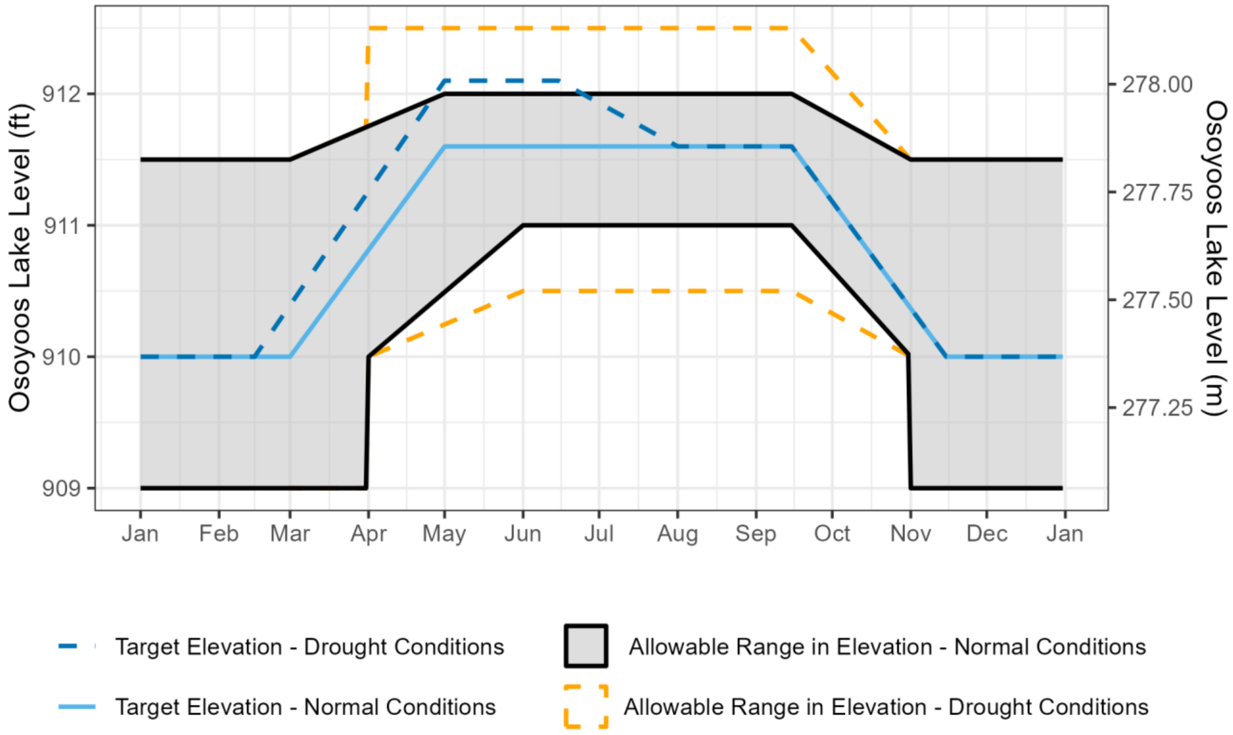

Figure 3.1 **Maximum, minimum, and target elevations for normal and drought conditions utilized in the hydrologic model**

The Zosel Dam operating procedures (Department of Ecology, 1990) define minimum instream flow requirements at the Okanogan River at Oroville streamflow gauge downstream of Zosel Dam, as summarized in Table 3.1. The IJC's order of approvals take precedence over minimum instream flow requirements. To handle this in the hydrologic model, a higher weight was placed on the lake level goals such that outflow from the lake would be less than the minimum instream flow requirements if needed to allow the model to maintain the lake level goals.

Table 3.1 Minimum instream flow requirements downstream of Zosel Dam

Date	Instream Flow Requirement (ft^3/s)	Instream Flow Requirement (m^3/s)
Jan 1 – Mar 15	320	9.06
Apr 1	330	9.34
Apr 15	340	9.62
May 1	350	9.91
May 15 -June 15	500	14.16
July 1	420	11.89
July 15	350	9.91
Aug 1 – Aug 15	320	9.06
Sept 1 – Sept 15	300	8.49
Oct 1	330	9.34
Oct 15 – Nov 1	370	10.47
Nov 15 – Dec 15	320	9.06

3.1.3 Operation Constraints of Osoyoos Lake

The operation of Osoyoos Lake is primarily constrained by the balance between inflows and outflows. Inflows consist of regulated outflows from Okanagan Lake and tributary inflows between Okanagan Lake and Osoyoos Lake.

Outflows from Osoyoos Lake are predominantly regulated by Zosel Dam, which features four independently operated sluice gates, each measuring 25 feet wide by 12 feet high, with an invert elevation of 906.0 feet NAVD29 (Acres International Limited, 1987). The dam also includes two fish passageways, each 8 feet (2.4 m) wide and 73 feet (22.3 m) long, located on either side of the spillway. Outflow regulation is primarily managed through the sluice gates, while the fish passageways are assumed to remain open. Additionally, the dam is equipped with a concrete spillway with a crest elevation of 913 feet NAVD29 (278.282 m), providing an emergency spill capacity during high lake level conditions.

The outflow through the sluice gates at Zosel Dam was represented in the Raven model using a series of rating curves. These curves define the relationship between outflows and key factors influencing headwater conditions (i.e., Osoyoos Lake levels) and tailwater conditions at the dam. Similkameen River flows play a critical role in this process, as high flows can raise tailwater levels at Zosel Dam, restricting discharge from the lake. In extreme cases, exceptionally high

Similkameen flows can even cause flow reversal, further elevating Osoyoos Lake levels. Three distinct flow conditions were considered for modelling Osoyoos Lake:

- **Regular Conditions:** Outflow at Zosel Dam is inlet-controlled, meaning that Okanogan River flow is governed solely by Osoyoos Lake levels and the position of the sluice gates. Downstream of the dam, the tailrace remains in a free-flow state, with no influence from Similkameen River flows on outflows at Zosel Dam.
- **Backwater Conditions:** Outflow at Zosel Dam is outlet-controlled, where the inflow is faster than the outflow through the Dam. This condition is created due to higher tailwater level at the dam, caused by flow from the Similkameen River entering the Okanogan River through a connection channel upstream of Driscoll Island.
- **Backflow Conditions:** Under extreme conditions, Similkameen River flows become high enough to raise the tailwater at Zosel Dam higher than the headwater levels, causing flow reversal at Zosel Dam and further elevating Osoyoos Lake levels.

3.1.3.1 Regular Conditions

When Similkameen River flow is normal or low, approximately below 10,000 ft^3/s (283 m^3/s), the sluice gates at Zosel Dam are adjusted to maintain Osoyoos Lake levels within the prescribed rule curves (Figure 3.1) while balancing water usage needs and minimum instream release requirements. Depending on lake inflows, the sluice gates may be fully lifted to allow natural outflow, or they may be adjusted to regulate lake levels.

Under these conditions, outflow at Zosel Dam can be estimated using the sluice gate equation, assuming a free-flowing tailwater:

$$Q = C \cdot W \cdot B \cdot \sqrt{2gh} \qquad \text{Eqn (1)}$$

where:

- C is the discharge coefficient, typically ranging from 0.5 to 0.7,
- W and B represent the width and opening depth of the sluice gate, respectively,
- g is the gravitational constant,
- h is the hydraulic head differential between the headwater and tailwater.

Historically, the sluice gates have generally remained open to minimize interference with natural outflows but have been adjusted as needed to manage lake levels based on forecasted inflows. Osoyoos Lake levels have typically been maintained below 912 ft NAVD29 (277.978 m).

In the Raven model, the discharge coefficient was set to 0.6. When the Osoyoos Lake level was below 912 ft NAVD29 (277.8978 m), the model assumed two sluice gates were partially opened to 4.5 ft (B = 4.5 ft). When lake levels exceeded 912 ft, the model assumed all four sluice gates were fully opened to 12 ft (B = 12 ft).

3.1.3.2 Backwater Conditions

Representing outflow from Zosel Dam in the Raven model under backwater conditions required establishing a relationship between outflow and the factors influencing the hydraulic head differential upstream and downstream of the dam. Developing this relationship necessitated a comprehensive understanding of the hydraulic conditions, achieved through a combined approach:

- regression analysis of gage data to derive empirical relationships based on observed phenomena, and
- hydraulic modelling to explain the underlying physical processes governing flow behaviour (detailed model description can be found in Appendix A).

Physical Processes

The Similkameen River can exchange flow with the Okanogan River through a connection channel upstream of Driscoll Island. This channel has a nearly flat slope (0.09%) and a general depth of 4.7 m and width of 46 m; flow direction in the connection channel depends on the water levels in each river, allowing for bidirectional exchange. In 2010, a flow distribution weir was installed in the channel to prevent westbound flow from the Okanogan River into the Similkameen River while allowing eastbound flow from the Similkameen into the Okanogan to continue largely unimpeded.

When Similkameen River flows exceed approximately 10,000 ft^3/s (283 m^3/s), water begins to enter the connection channel, creating a backwater effect at the confluence with the Okanogan River. If high flows persist or increase, this backwater effect can propagate upstream to Zosel Dam, raising tailwater levels at the sluice gates and impeding outflows from Osoyoos Lake. Although backwater effects can occur even when Osoyoos Lake levels are below 912 ft NAVD29 or Similkameen flows are below 10,000 ft^3/s, their impact on lake levels under these conditions is generally managed by sluice gate operations.

The occurrence and severity of backwater effects are influenced by multiple hydraulic factors beyond just flow magnitudes. Key factors include but are not limited to the duration and timing of flow events (rising or falling limb of a hydrograph), the position of the sluice gates at Zosel Dam, and downstream hydraulic conditions. Given this complexity, observed flow data at Zosel Dam exhibit notable scatter and hysteresis (Figure 3.2), necessitating the establishment of threshold conditions for defining a rating curve under the backwater condition. These thresholds were determined through visual inspection of historical data and hydraulic analysis using a one-dimensional (1D) model.

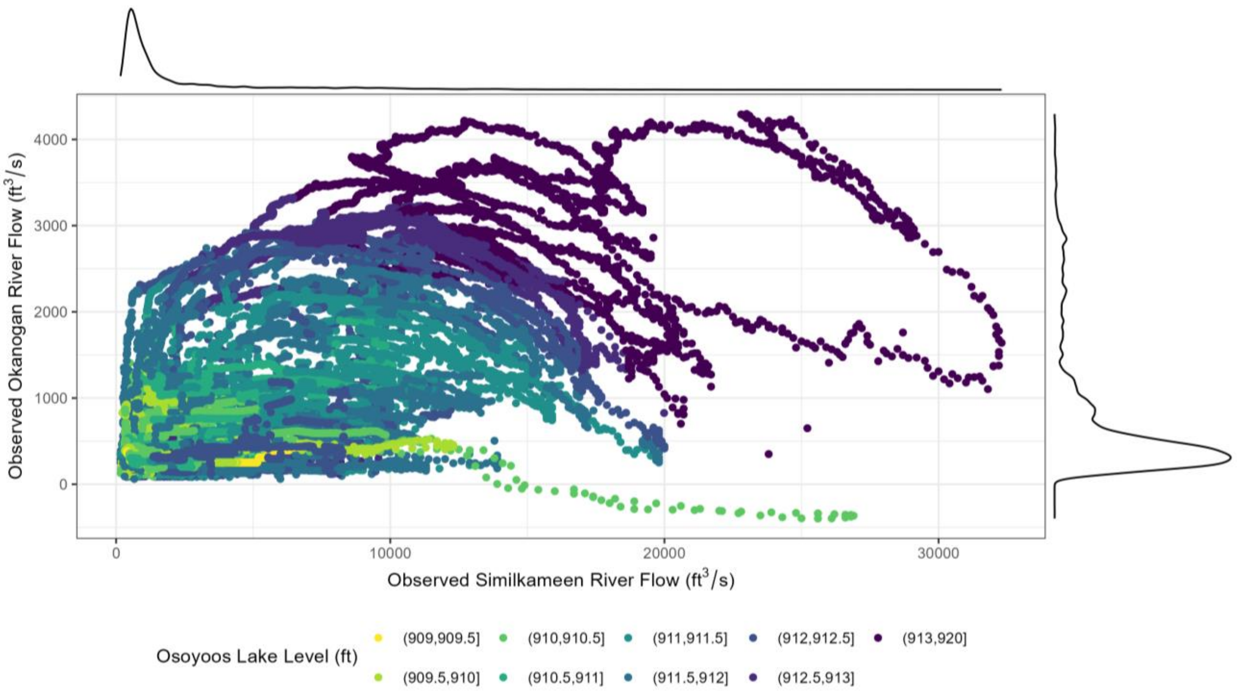

Figure 3.2 **Historical Osoyoos Lake levels, Okanogan River flows and Similkameen River flows.**

To refine these threshold conditions and evaluate the influence of backwater and backflow on Osoyoos Lake levels, NHC developed a 1D hydraulic model using HEC-RAS (V6.5). This model was used to verify the data-driven regression approach for characterizing outflows at Zosel Dam in responses to the varying Similkameen flow and Osoyoos Lake level conditions.

Regression Analysis

Outflows from Zosel Dam are largely governed by the relationship between Osoyoos Lake levels and Similkameen River flows. The 2010 Study: Demonstration of Factors that Govern Osoyoos Lake Levels During High Water Periods (referred to as Study 7) applied a multivariate linear model to predict Zosel Dam outflows using observed daily data of Osoyoos Lake levels and Similkameen River flow (Summit Environmental Consultants, 2010)

Building on this methodology, NHC adopted a multivariate regression approach using concurrent data from gages listed in Table 3.2. Prior to the regression analysis, data from the USGS gage at Okanogan River at Oroville was assessed to confirm that backwater and backflow effects were captured in the manually recorded flow and stage data[1]. A combination of daily and hourly data was used to maximize the available data for the regression analysis.

Table 3.2 Gauge data used in multivariate regression development

Gauge ID	Name	Location	Type	Period of Record
USGS 12439500	Okanogan River at Oroville, WA	Okanogan River downstream of Zosel Dam and the railway bridge	Daily	1990 – 2007
			Hourly	2008 - 2024
			Manually collected flow and stage data[1]	1990 - 2024
USGS 12439000	Osoyoos Lake Near Oroville, WA	Osoyoos Lake	Daily	1990 - 2007
			Hourly	2008 – 2024
USGS 12442500	Similkameen River Near Nighthawk, WA	Similkameen River upstream of the model boundary condition	Daily	1990 - 2007
			Hourly	2008 – 2024

Notes:

1. Flow and stage field measurements were collected periodically by USGS at this station.

The regression analysis used cross-validation and separate training and test datasets (Figure 3.3 and Figure 3.4) to evaluate the fit and uncertainty of the multivariate linear model. Since the Raven model could not account for all influencing factors, some variance in predictions was expected due to interannual variability in the dataset. Cross-validation helped mitigate overfitting and improve generalizability, ensuring the model performed consistently across different data subsets. This approach also quantified prediction uncertainty and assessed the model's ability to capture variability in outflows at Zosel Dam.

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[1] USGS manually collects flow and stage data at this location and develops modified rating curves that account for backwater and backflow effects. Additionally, an auxiliary gage downstream of the main gage measures the water surface gradient between the gage and the confluence of the connection channel and Okanogan River. By analyzing this water surface gradient, different rating curves were applied to convert stage measurements into flow estimates under both normal flow conditions and backwater/backflow conditions. As a result, the gage data was deemed suitable for developing regression relationships between Osoyoos Lake levels, Similkameen River flow, and outflows from Zosel Dam.

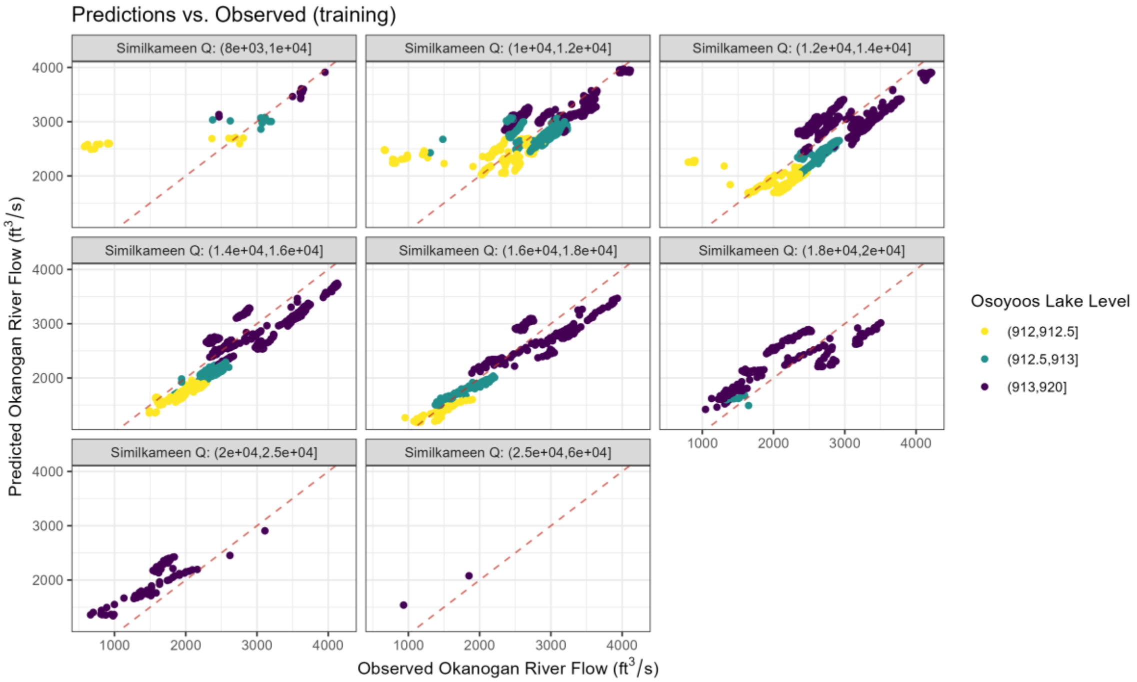

Figure 3.3 Predicted vs. Observed Okanogan River flow of training dataset

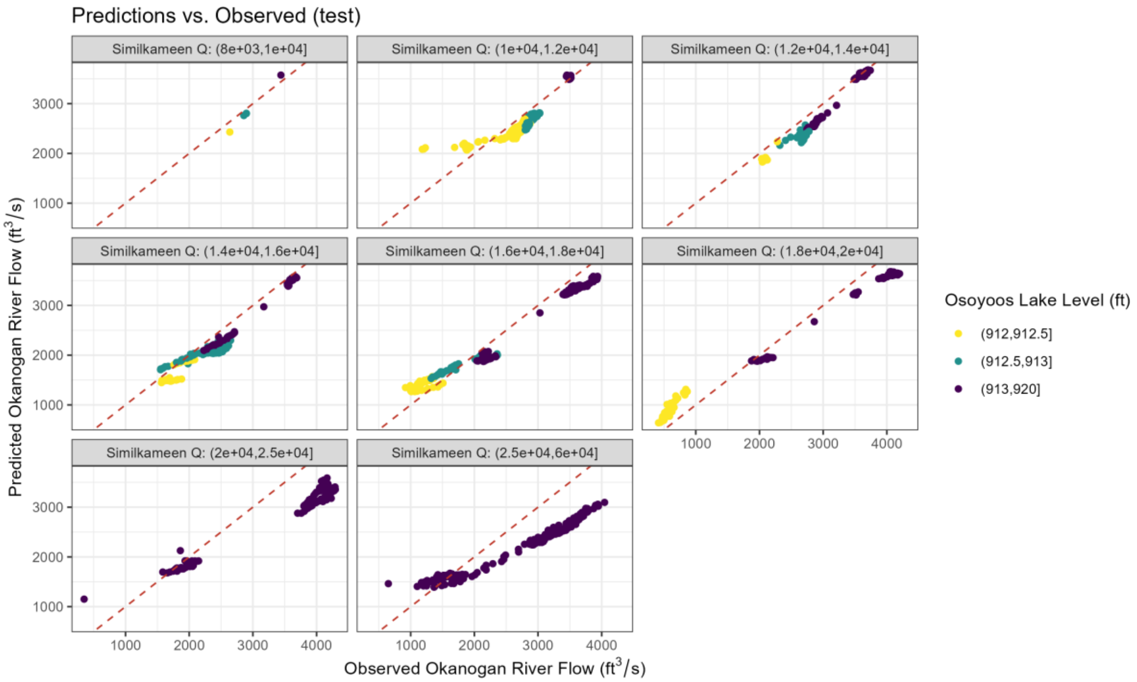

Figure 3.4 Predicted vs. Observed Okanogan River flow of test dataset

The final regression model yielded the following predictive relationship for outflows at Zosel Dam, applicable when Osoyoos Lake levels exceed 912 ft NAVD29 (277.978 m) and Similkameen River flow surpasses 10,000 ft^3/s (283 m^3/s).

Imperial $$Q_{outflow} = 744.47 \cdot WSE_{Osoyoos\ Lake} - 0.173 * Q_{Similkameen\ River} - 674871.24$$

SI $$Q_{outflow} = 78.181 \cdot WSE_{Osoyoos\ Lake} - 0.151 * Q_{Similkameen\ River} - 21629.88$$

3.1.3.3 Backflow Conditions

Backflow conditions occur when Similkameen River flows raise tailwater levels at Zosel Dam above the headwater level controlled by Osoyoos Lake, reversing the hydraulic gradient and forcing flow upstream. Under these conditions, lake levels are expected to rise due to net positive inflows, with the potential for overtopping of banks and flooding of adjacent floodplains.

Backflow events can occur under various combinations of Similkameen River and Okanogan River flows, but their impact on Osoyoos Lake levels is highly variable. When Similkameen River flows exceed 15,000 ft^3/s (509.7 m^3/s) in combination with relatively high Okanogan River flows above 2119 ft^3/s (60 m^3/s), backflow has been observed, such as during the November 2021 event. Alternatively, backflow can also occur when Similkameen River flows become high (e.g., exceed 20,000 ft^3/s or 566.3 m^3/s), regardless of Okanogan River discharge. However, the resulting lake level response varies depending on several additional factors.

Backflow events driven by high Similkameen River flows but low Okanogan River flows do not always lead to significant lake level rise. The extent of backflow-induced lake level increases is influenced by in-channel storage capacity, sluice gate operations at Zosel Dam, and antecedent lake conditions. In some cases, a portion of the backflow is temporarily stored within the channel, delaying or dampening its impact on lake levels. Additionally, lake levels preceding a backflow event can determine the available storage capacity and the rate at which water accumulates.

Higher concurrent Okanogan River flows further alter backflow dynamics. While they may reduce the reverse flow effect, they can also enhance the backwater effect, impeding outflows from Osoyoos Lake and resulting in elevated lake levels. The interplay between these factors highlights the inherently variable nature of backflow, where lake level responses are not dictated by a single threshold but by a combination of flow conditions, hydraulic interactions, and operational decisions.

As illustrated by Figure 3.2, outflows at Zosel Dam exhibit considerable variability under backflow conditions triggered by high Similkameen flow events. However, lake levels generally exceed 912 ft NAVD29 during these events. In a few rare cases, lake levels remained below the 912 ft operational threshold, likely due to factors such as antecedent conditions, overbank flooding, and operation of sluice gates, all of which contribute to the dynamic nature of backflow events. These factors have proven difficult to isolate and quantify even with the 1D hydraulic model (see details in Appendix A).

The 1D hydraulic model developed by NHC highlighted the challenges of event-based calibration, as it exhibited variability in calibration success and difficulty in isolating the individual effects of various factors. The backflow process is inherently three-dimensional, involving complex interactions such as turbulence mixing, overbank storage, and dynamic flow exchanges that a 1D model cannot fully capture. However, the initial decision to use a 1D model was driven by the need for long-term simulation, which ultimately proved unfeasible due to computational constraints and insufficient historical operational records. Even at the 1D scale, the complexity of the hydraulics resulted in long simulation times, making continuous, long-term modelling impractical.

Additionally, the high variability between backflow events—driven by factors such as antecedent conditions, fluctuating flow directions, and transient hydraulic responses—further complicated event-based analyses. Given this variability, a long-term calibration approach would likely be more effective than individual event-based calibration, as it would better account for the range of conditions influencing backflow behavior.

Given these challenges, the regression relationship was adopted to simulate backflow conditions with Raven, as the regression showed reasonable fit under these backflow conditions. Despite the scatter in both observed data and model outputs, most backflow events have historically led to elevated lake levels, supporting the suitability of this approach for predicting future lake levels under changing climate conditions.

3.2 Climate Change Downscaling and Simulations

Phase 1 of the Osoyoos Lake Change Vulnerability Study adopted an ensemble of downscaled global climate models from the CanESM2 global climate model (GCM) for a single representative concentration pathway 8.5 from the Coupled Model Intercomparison Project (CMIP) 5. For Phase 2, NHC used the most recent CMIP6 projections, analyzing multiple emission scenarios. This section describes the selection and downscaling of climate projections and the subsequent modelling of both the Okanagan and Similkameen basins using the new climate projections.

3.2.1 Global Climate Models and Downscaling Methodology

Prior to commencing the Phase 2 study, NHC completed a scoping study (NHC, 2024) which reviewed and recommended the required resolution of the climate data, the data sources, and downscaling methodology.

A multivariate CMIP6 dataset (CanDCS-M6) developed by the Pacific Climate Impact Consortium (PCIC) was used as the basis for the 500 m downscaled climate projections in this study. NHC downscaled five GCMs for two different emission scenarios: shared socioeconomic pathway SSP2-4.5 and SSP5-8.5 representing a medium and high emission scenario respectively. The five GCMs downscaled were TaiESM1, NorESM2-LM, CNRM-ESM2-1, MPI-ESM1-2-HR, and FGOALS-g3 which are the 5 most representative GCMs of all 26 GCMs downscaled by PCIC for British Columbia.

The PCIC datasets for daily precipitation and temperature (minimum and maximum) were downscaled to 500 m grids using the same statistical downscaling methodology used for previous climate projections used in Phase 1 of the study (NHC, 2020). The methodology uses the Quantile Delta Mapping (QDM) bias-correction statistical downscaling algorithm from PCIC's ClimDown R package.

3.2.2 Long Term Simulations

To simulate the long-term conditions (1945 to 2100) on the Similkameen River and Okanagan basin, including Osoyoos Lake, the 500 m climate data was aggregated to an irregular grid with one point corresponding to each hydrologic response unit within the model, in an identical manner as the original gridded observation dataset.

Changes in water demand within the model were generated by the Agricultural Water Demand Model for the most representative GCM (TaiESM1) for both SSP2-4.5 and SSP5-8.5. Water demand was aggregated to a subbasin level using the same methodology as in the initial model development.

Both the Similkameen and Okanagan hydrological models were then run from 1950 to 2100 using the 10 different climate scenarios (5 GCMs under 2 SSPs). Incorporating lake operations required running the Okanagan hydrologic model multiple times:

- The first run forecasts the required regulation constraints for Okanagan Lake based on snow pillow information and freshet inflows.
- The second run forecasts the required regulation constraints for Osoyoos Lake depending on Okanagan Lake inflow volumes and stages.
- The third and final run simulates lake levels on Osoyoos Lake with the regulation constraints (i.e. lake elevation constraints) provided by the second run to produce the ultimate simulations used in the analysis.

4 RESULTS

The following section provides an overview of the projected hydrologic changes to the Okanagan and Similkameen watersheds (Section 4.1) to provide context for the resulting projected changes to the Okanagan and Osoyoos drought condition and Osoyoos lake levels (Section 4.2).

4.1 Projected Hydrologic Changes

Figure 4.1 and Figure 4.2 show the projected daily average temperature and monthly average precipitation for the Okanagan and Similkameen basin based on the five global climate models for SSP2-4.5 and SSP5-8.5. The projections are shown for five 30-year climatological periods spanning from 1981 to 2100. Table 4.1 and Table 4.2 summarize the annual changes in precipitation and temperature compared to the baseline period (1981-2010) for both basins.

Figure 4.1 indicates that temperature is expected to warm from present day to end of century in both basins, with larger changes expected under SSP5-8.5 compared to SSP2-4.5 particularly for the end of century period. The period of temperature below freezing in both watersheds is expected to shorten over time. The freezing period is projected to start later in the year (e.g., shifting from November to December) and ending earlier (e.g., February instead of March in the Okanagan and February/March instead of April in the Similkameen) by end of century. The temperature projections show a small downscaling artefact at the 1st of some of the months (such as July 1st). This sharp increase or decrease in values is the result of the original downscaling methodology used by PCIC which uses monthly values instead of rolling averages.

Precipitation projections (Figure 4.2) demonstrate higher variability in both watersheds by time period and SSP. In general, the precipitation projections indicate more precipitation throughout the year for the end of century scenario with the exception of July and August when precipitation is expected to decrease. The largest increases in precipitation are expected in the November to January period, particularly under SSP5-8.5.

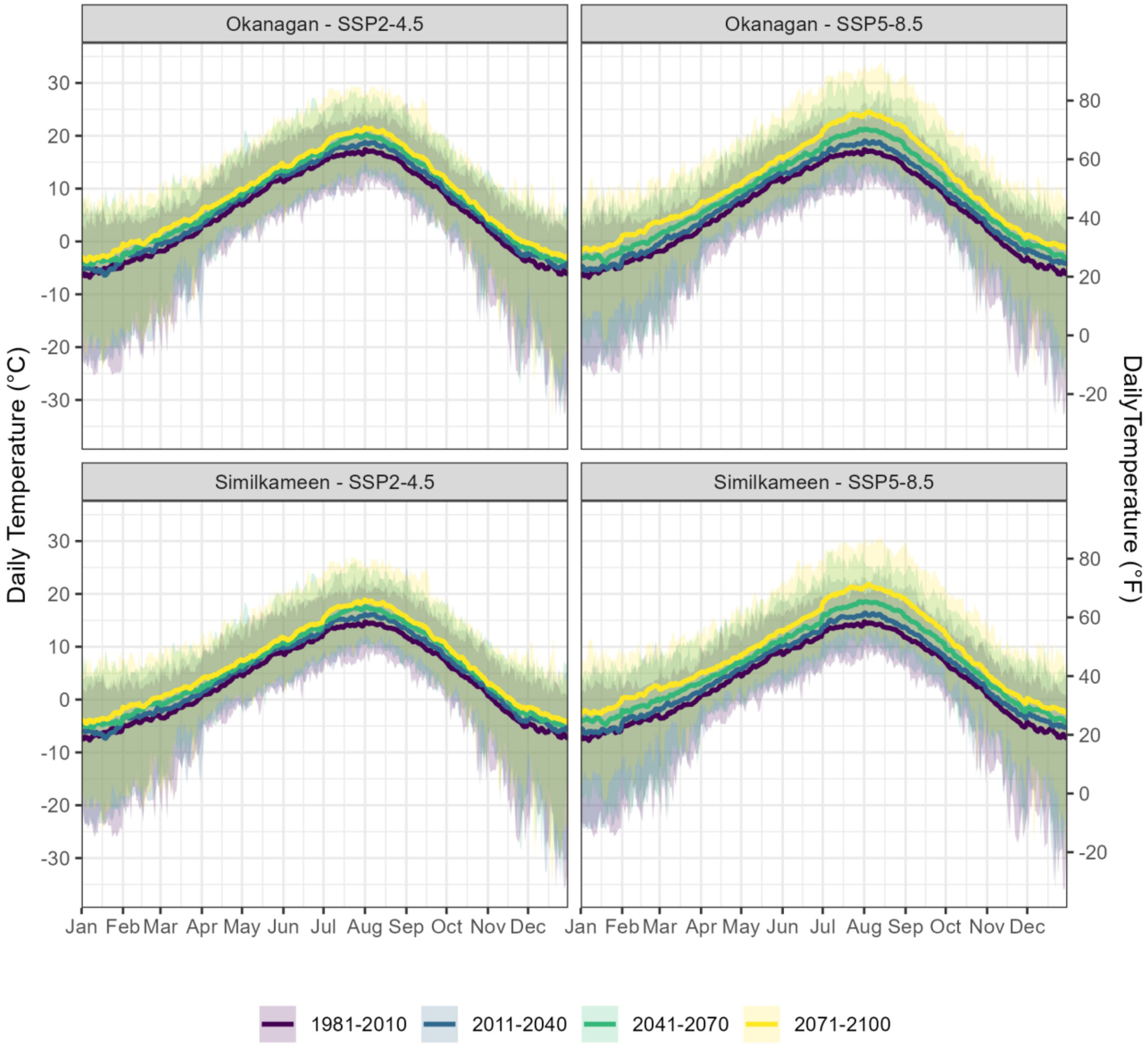

Figure 4.1 **Daily average basin wide temperatures of the Okanagan and Similkameen basins under SSP2-4.5 and SSP5-8.5. The lines represent the average of the 5 GCMs for each 30 year period while the ribbons represent the minimum and maximum daily average temperature.**

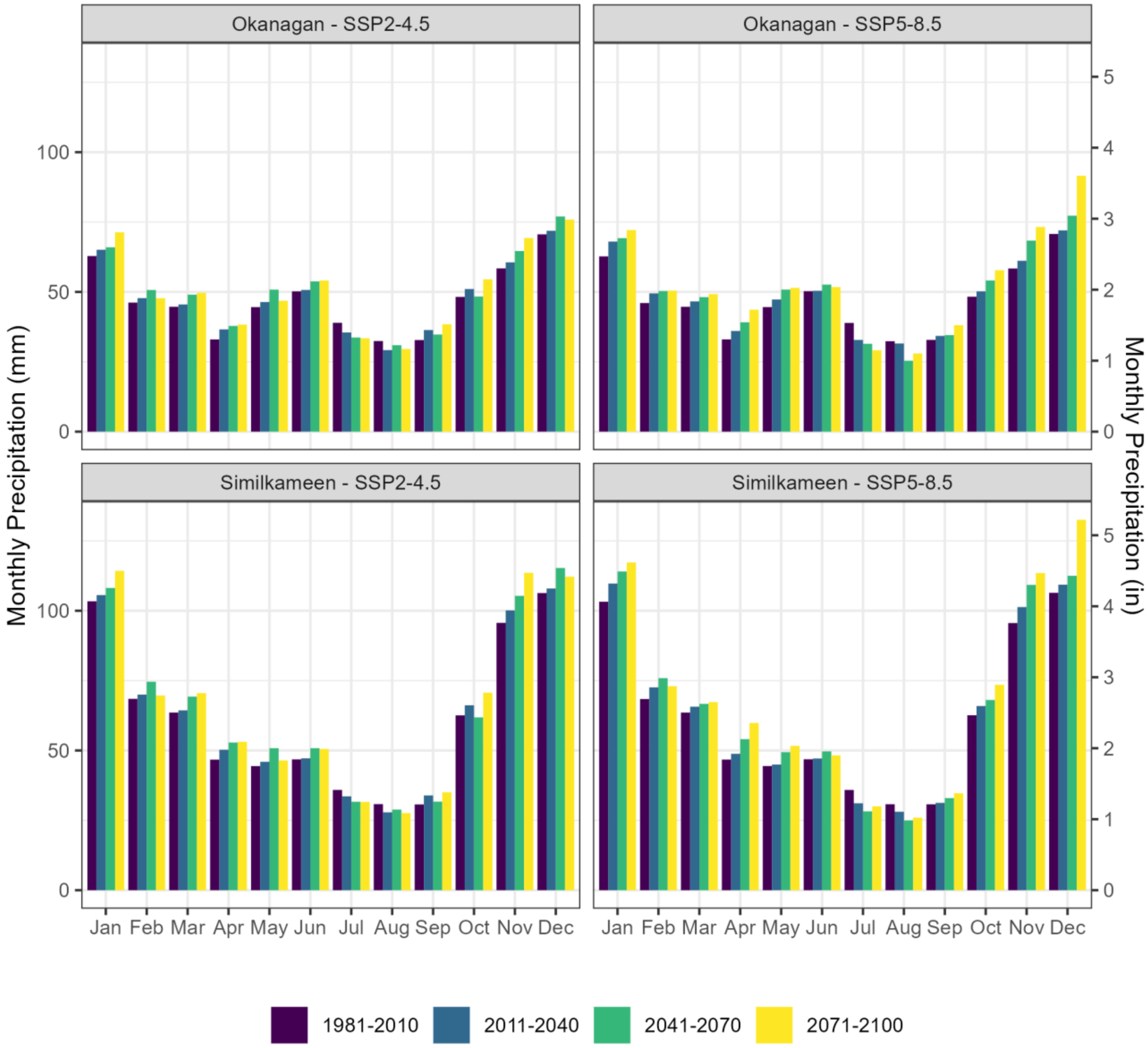

Figure 4.2 **Average monthly precipitation in the Okanagan and Similkameen basins under SSP2-4.5 and SSP5-8.5**

Table 4.1 Percent increase in average annual precipitation from the baseline period (1981-2010) for the Okanagan and Similkameen basins under SSP2-4.5 and SSP5-8.5

Period	% Increase in Annual Precipitation (Okanagan)		% Increase in Annual Precipitation (Similkameen)	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
2011-2040	2%	3%	2%	3%
2041-2070	6%	7%	6%	7%
2071-2100	8%	13%	8%	13%

Table 4.2 Increase in average annual temperature (°C/°F) from the baseline period (1981-2010) for the Okanagan and Similkameen basins under SSP2-4.5 and SSP5-8.5

Period	Increase in average annual temperature (Okanagan)		Increase in average annual temperature (Similkameen)	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
2011-2040	1.9°F (1.1°C)	2.3°F (1.3°C)	1.9°F (1.1°C)	2.3°F (1.3°C)
2041-2070	3.9°F (2.2°C)	5.4°F (3.0°C)	3.9°F (2.2°C)	5.4°F (3.0°C)
2071-2100	5.7°F (3.1°C)	9.1°F (5.1°C)	5.7°F (3.1°C)	9.0°F (5.0°C)

The increase in winter precipitation coupled with a shorter period below freezing, results in changes to the accumulation and melt of snow (Figure 4.3). The average snowpack is projected to decrease into the future, indicating that despite more precipitation in the winter, a greater proportion of it is falling as rain instead of snow. The snowpack is also expected to melt earlier in the year due to warmer temperatures.

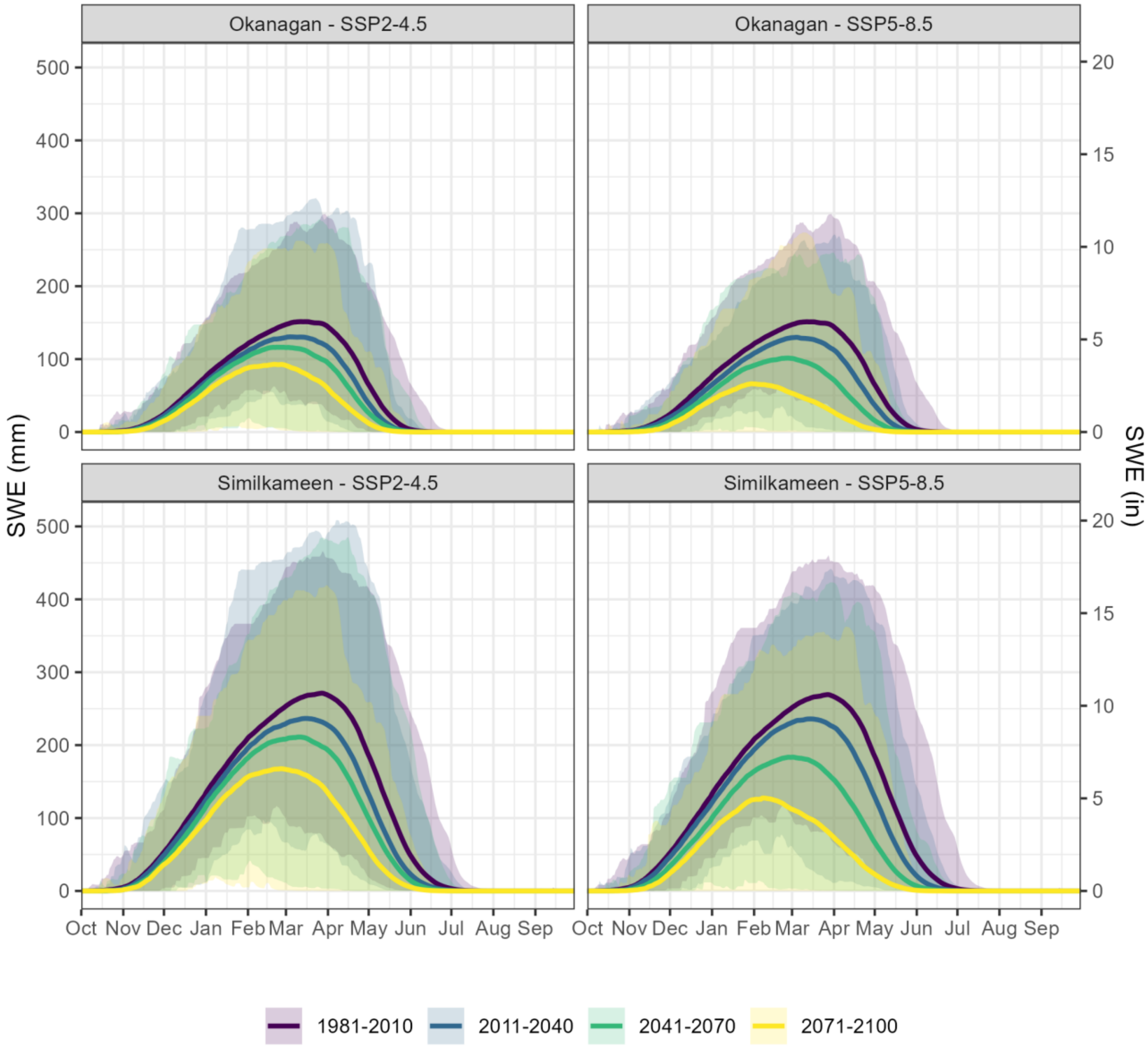

Figure 4.3 **Snow water equivalent (SWE) accumulation and melt in the Okanagan and Similkameen basins under SSP2-4.5 and SSP5-8.5. The lines represent the average of the 5 GCMs for each 30-year period while the ribbons represent the minimum and maximum SWE values.**

The smaller snowpack and earlier melt coupled with an increase in winter precipitation falling as rain instead of snow impacts both the annual hydrograph of the Similkameen River and inflows to Okanagan Lake (Figure 4.4). The peak of the freshet is projected to occur earlier in the year, with a lower magnitude due to the changes in snow accumulation and melt. Another notable change is the increased flows during the fall and winter period, as a result of more rain or rain on snow events occurring.

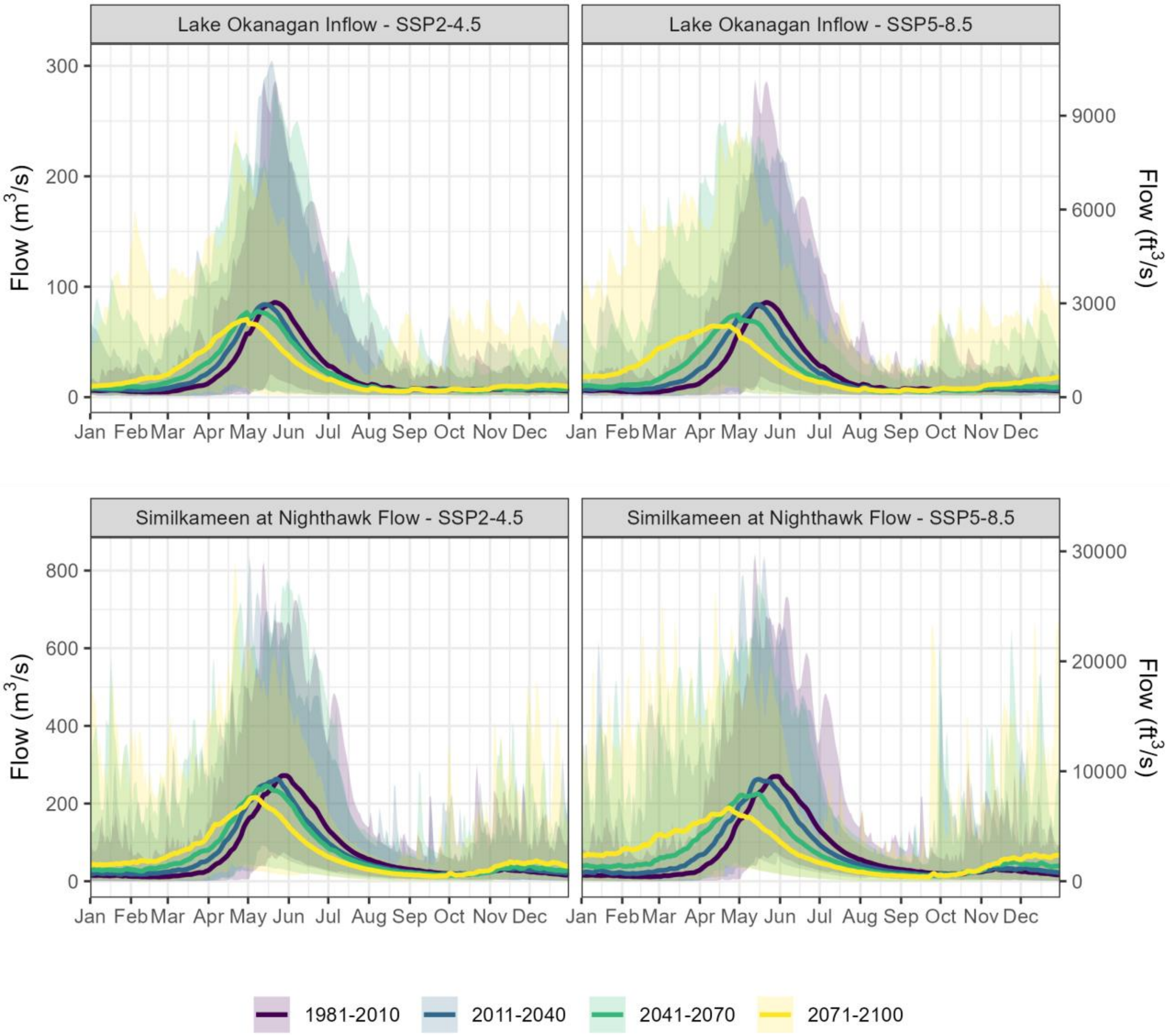

Figure 4.4 Average daily hydrograph (line) and minimum and maximum flows (ribbons) at the Similkameen River at Nighthawk and inflows to Okanagan Lake under SSP2-4.5 and SSP5-8.5 for each 30 year period

In the Raven model, present-day operational rules were applied under future climate conditions on Okanagan Lake. Due to projected shifts in inflow timing under projected climate conditions, the model revealed a disconnect between existing operational rules and inflow patterns, resulting in higher lake levels while generally maintaining the timing and magnitude of outflows, as shown in Figure 4.5.

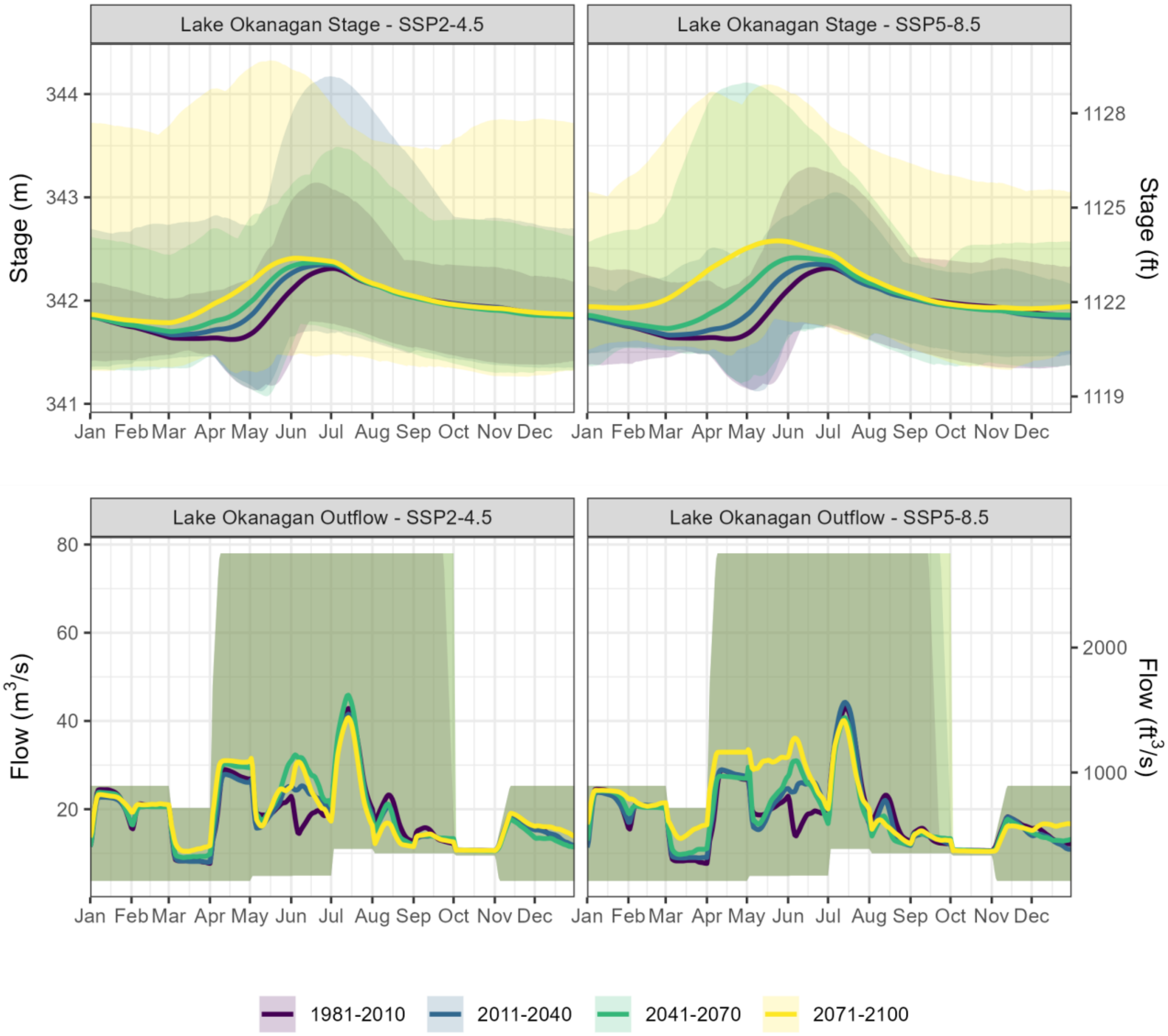

Figure 4.5 Projected Okanagan Lake levels and outflows under SSP2-4.5 and SSP5-8.5

The assumption that Okanagan Lake regulation would remain unchanged until 2100 is a limitation of this Phase 2 study. Okanagan Lake operations are expected to evolve, as suggested in previous work (NHC, 2020), which may change the timing of outflow from the lake and ultimately impact operations of Osoyoos Lake. NHC recommends that future work consider changes to operation on Okanagan Lake to understand the impact on current operations of Osoyoos Lake.

4.2 Projected Changes to the Drought condition and Osoyoos Lake Levels

The following section outlines projected changes to both the Okanagan Basin and Osoyoos Lake drought condition, as well as projected changes to Osoyoos lake levels. To facilitate interpretation, average values have been reported throughout this section except where noted.

4.2.1 Okanagan Basin Drought Condition

The projected hydrologic changes have illustrated that there is a shift in the timing of the inflow hydrograph and lake levels of Okanagan Lake, which both influence the drought operation conditions for Osoyoos Lake. For a drought to be declared on Osoyoos Lake, condition 8a (April to July volume less than 1.0 million acre feet) must be met on the Similkameen and the following conditions met on the Okanagan: 1) the net inflow to Okanagan Lake for the period from April through July is less than 195,000 acre-feet (Condition 8bi), or 2) the level of the level of Okanagan Lake fails to reach 1122.6 ft (342.16 m) during June or July (Condition 8bii). Net inflow to Okanagan Lake was defined by the change in storage and outflow (i.e. considers demand and lake evaporation and precipitation).

4.2.1.1 Condition 8bi

Figure 4.6 shows the probability density of net inflow volume for the period from April through July for historical conditions (1950 to 2019) and future conditions (2020-2100) for both SSPs. The frequency of meeting Condition 8bi is projected to increase from 15% of years during the historical conditions to 22% of years under SSP2-4.5 for the future conditions. Under SSP-8.5, the frequency of meeting Condition 8bi increases further, with 31% of the years projected to fall below the threshold during the future period. For context, the observed record from 1987 to present day (38 year period), indicates that Condition 8bi has been met 7 times (18%).

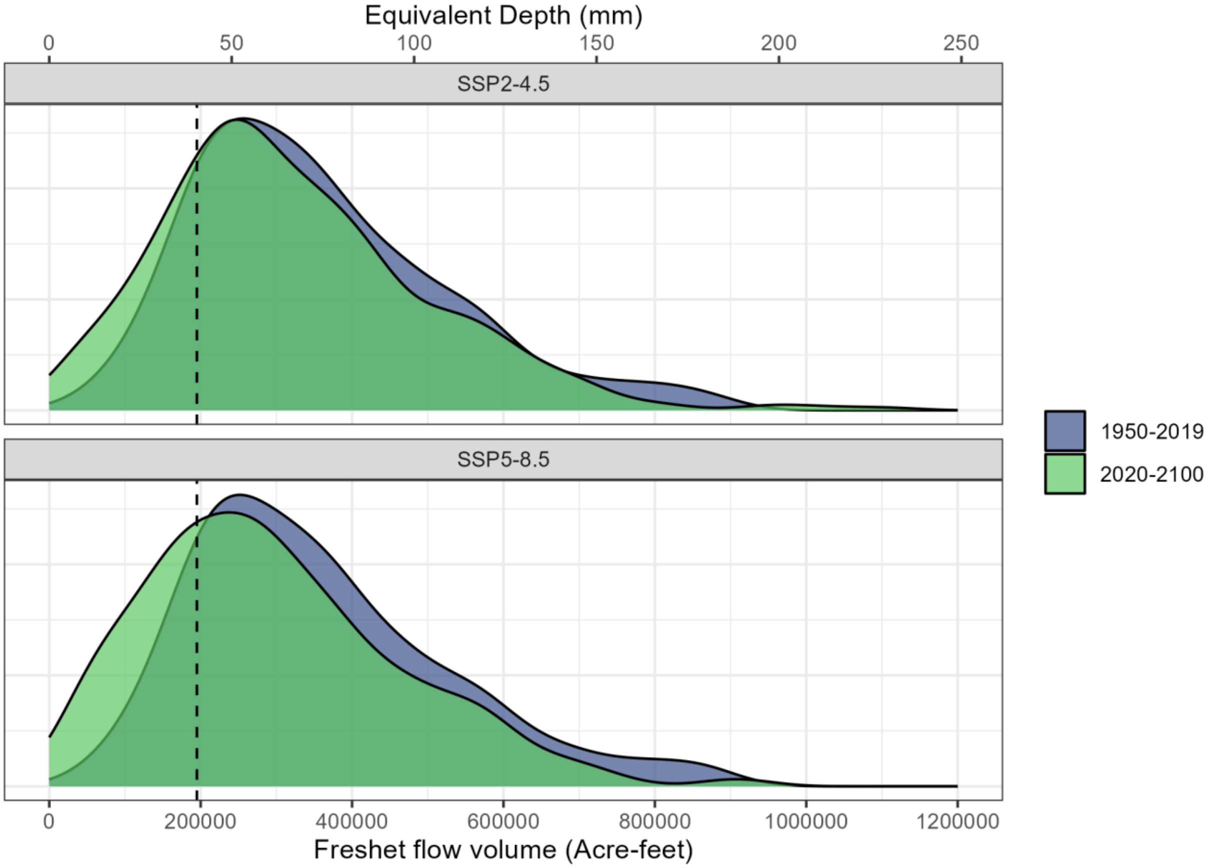

Figure 4.6 **Probability density of net inflow volume to Okanagan Lake for the April-July period, separated by historical and future period. The dashed line indicates the threshold net inflow volume of 195,000 acre-feet. Equivalent depth refers to the total freshet flow volume represented by uniform water depth (in mm) over the Okanagan Lake watershed area.**

The analysis revealed that under SSP5-8.5, the freshet net inflow volume dropped below zero in three (3) separate years, likely due to minimal or no snowpack accumulation over the winter period.

The simulated net inflow volumes were further split into five 30-year climatological periods as shown in Figure 4.7. These results indicate that the most significant shift in freshet volume distribution occurs during the final climatological period (2071–2100), particularly under SSP5-8.5. However, it is important to note that uncertainties associated with projected climate forcing increase with each subsequent projection period. As a result, while the largest changes appear in the later climatological periods, they also represent the most uncertain projections.

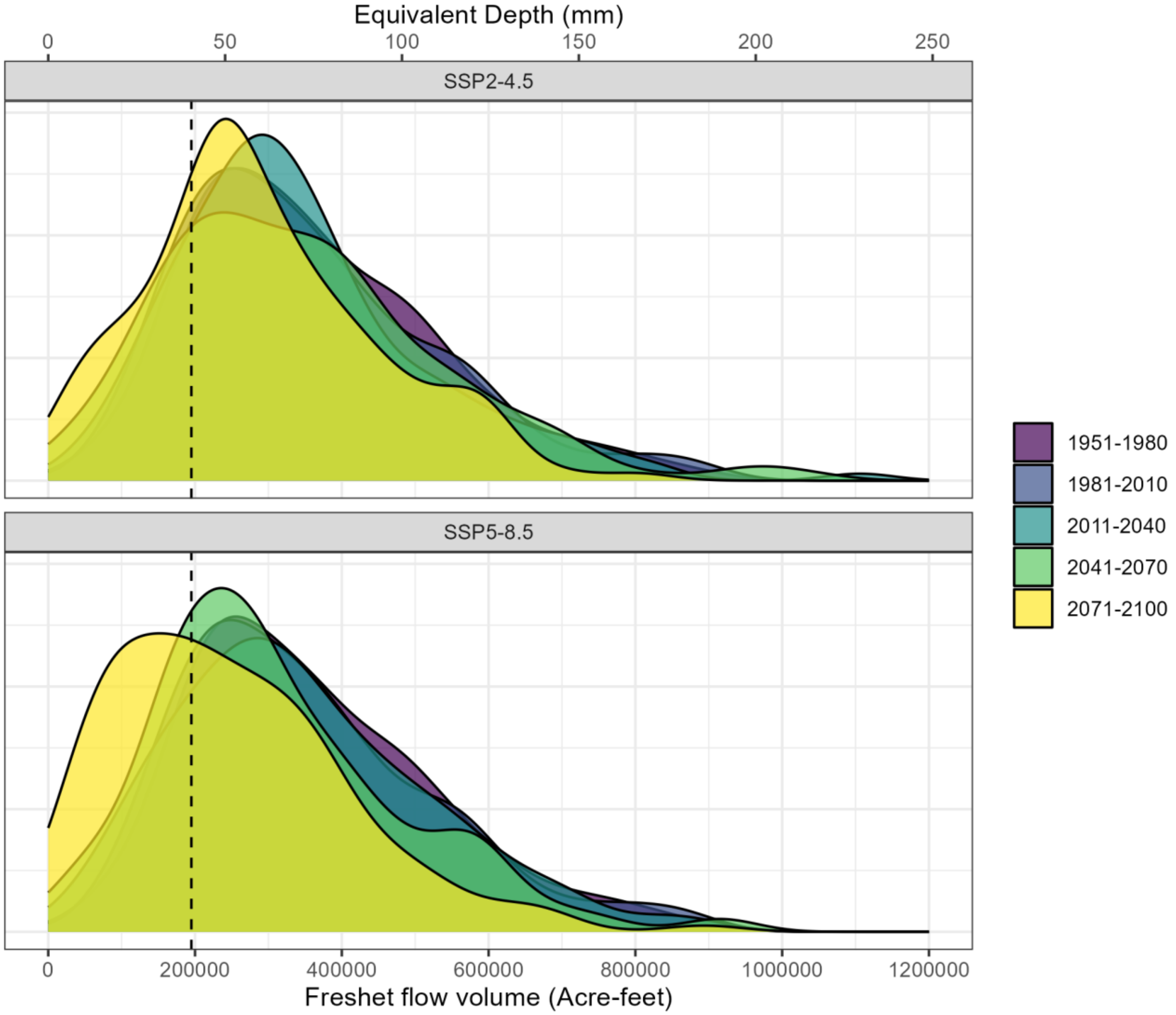

Figure 4.7 Probability density of net inflow volume to Okanagan Lake for the April-July period, separated by 30-year climatological periods. The dashed line indicates the threshold net inflow volume of 195,000 acre-feet. Equivalent depth refers to the total freshet flow volume represented by uniform water depth (in mm) over the Okanagan Lake watershed area.

The average percentage of years with April to July volumes below 195,000 acre-feet, as shown in Table 4.3, demonstrates a consistent increase over the projected time scale.

Table 4.3 Average percent of years below the 195,000 acre-ft drought condition threshold for Okanagan Lake

Period	% Years Below 195,000 acre-ft Drought condition	
	SSP2-4.5	SSP5-8.5
1951-1980	13%	13%
1981-2010	16%	15%
2011-2040	19%	20%
2041-2070	21%	25%
2071-2100	25%	43%

A non-parametric Chi-Square test was used to assess the statistical significance of changes in the frequency of drought and non-drought conditions under future climate scenarios as shown in Table 4.4 and Table 4.5. Using a probability value (p-value) of 0.05 for null hypothesis rejection, only the 2071-2100 period is statistically different than the 1951-1980 period under SSP2-4.5 whereas under SSP5-8.5 the 2071-2100 period is statistically different from all previous periods. Under SSP5-8.5 the 2041-2070 period is also statistically different from 1951-1980 and 1981-2010.

Table 4.4 Pairwise independent Chi-Square test results (p-values) for comparing the distributions of April to July inflow volume to Okanagan Lake by climatological periods for SSP2-4.5. Bold numbers indicate p-values for comparison with the prior climatological period.

Period	1951-1980	1981-2010	2011-2040	2041-2070
1981-2010	**0.41**	-	-	-
2011-2040	0.20	**0.76**	-	-
2041-2070	0.06	0.38	**0.65**	-
2071-2100	0.01	0.12	0.26	**0.58**

Table 4.5 Pairwise independent Chi-Square test results (p-values) for comparing the distributions of April to July inflow volume to Okanagan Lake by climatological periods for SSP5-8.5. Bold numbers indicate p-values for comparison with the prior climatological period.

Period	1951-1980	1981-2010	2011-2040	2041-2070
1981-2010	**0.61**	-	-	-
2011-2040	0.08	**0.29**	-	-
2041-2070	0.004	0.03	**0.33**	-
2071-2100	2.9E-9	9.09E-8	2.44E-5	**0.001**

4.2.1.2 Condition 8bii

As shown in Figure 4.5, maintaining current operational rules under a changing hydrological regime, particularly shifts in the timing of the annual hydrograph, would generally result in higher lake levels on Lake Okanagan. Figure 4.8 shows the probability density of maximum lake levels for the June and July period for historical and future conditions for both SSPs. For the future period, the frequency of meeting Criteria 8bii decreases under SSP2-4.5, with an average 17% of years predicted to fall below the threshold, compared to 20% during the historical period. Under SSP5-8.5, this proportion decreases further to 12% of years. For context, Okanagan Lake has been under this threshold 6 times (16%) from 1987 to 2024 in the observed record.

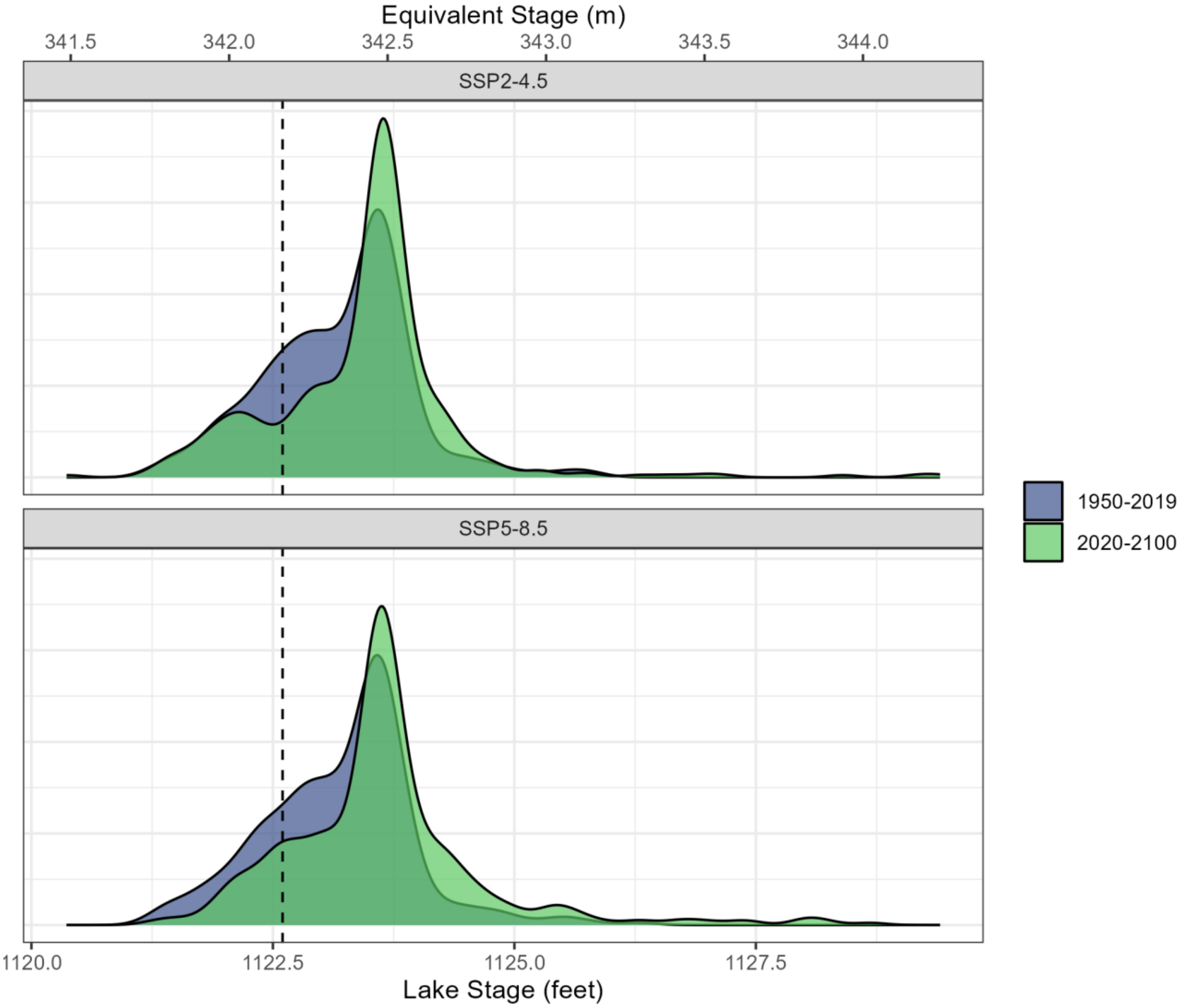

Figure 4.8 Probability density of maximum lake levels of Okanagan Lake in the June-July period, separated by historical and future period. The dashed line indicates the threshold lake level of 1122.6 ft.

Figure 4.9 presents the lake levels divided into 30-year climatological periods, illustrating how changes evolve over the projection periods. The results indicate a gradual shift, reflected in the percentage of years with June or July lake levels below 1122.6 ft, summarized in Table 4.6. This decreasing trend of lake levels falling below 1122.6 ft was further analyzed for statistical significance through Chi-Square tests.

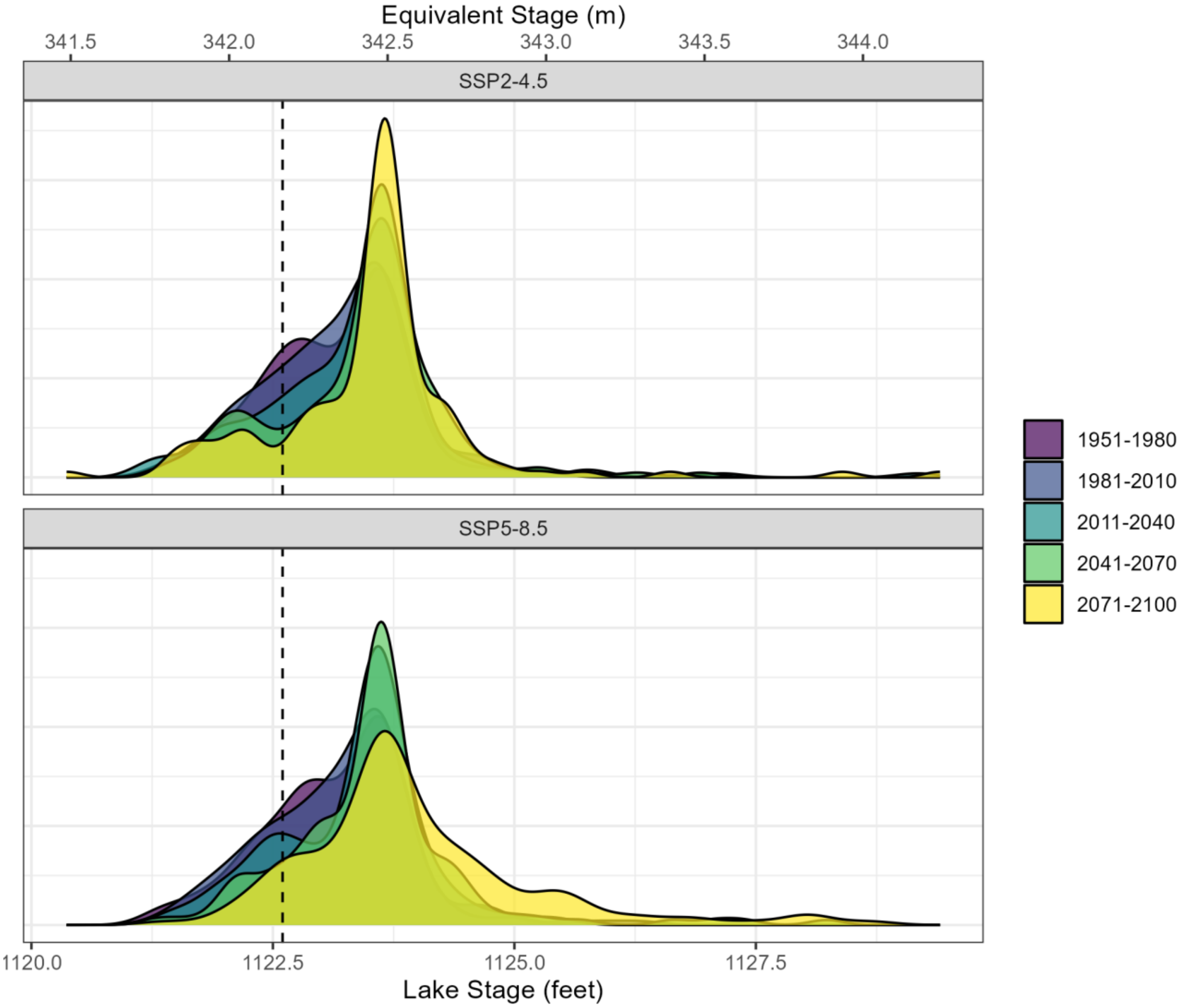

Figure 4.9 Probability density of maximum lake levels of Okanagan Lake in the June-July period, separated by 30-year climatological periods. The dashed line indicates the threshold lake level of 1122.6 ft.

Table 4.6 Percent of years below 1122.6 ft drought condition threshold for Okanagan Lake

Period	% Years Below 1122.6 ft Drought condition	
	SSP2-4.5	SSP5-8.5
1951-1980	21%	21%
1981-2010	21%	21%
2011-2040	19%	19%
2041-2070	17%	12%
2071-2100	15%	8%

The Chi-Square tests (Table 4.7 and Table 4.8), indicate that under SSP2-4.5 the frequency that drought condition is met is statistically similar for all periods. Under SSP5-8.5, the 2071-2100 period is statistically different from all previous periods except for 2041-2070.

Table 4.7 Pairwise independent Chi-Square test results (p-values) for comparing the distributions of June and July maximum Okanagan Lake levels by climatological periods for SSP2-4.5. Bold numbers indicate p-values for comparison with the prior climatological period.

Period	1951-1980	1981-2010	2011-2040	2041-2070
1981-2010	**1.0**	-	-	-
2011-2040	0.48	**0.48**	-	-
2041-2070	0.25	0.25	**0.76**	-
2071-2100	0.07	0.07	0.35	**0.63**

Table 4.8 Pairwise independent Chi-Square test results (p-values) for comparing the distributions of June and July maximum Okanagan Lake levels by climatological periods for SSP5-8.5. Bold numbers indicate p-values for comparison with the prior climatological period.

Period	1951-1980	1981-2010	2011-2040	2041-2070
1981-2010	**0.89**	-	-	-
2011-2040	0.67	**0.48**	-	-
2041-2070	0.05	0.024	**0.15**	-
2071-2100	0.001	0.0004	0.007	**0.25**

4.2.1.3 Drought condition for Okanagan Lake

Condition 8b criteria are met if either Condition 8bi (inflow volume) or 8bii (lake levels) is met. Section 4.2.1.1 and 4.2.1.2 reveal that the two conditions are projected to have diverging trends in the frequency of occurrence: a likely decrease in net inflow volume and a gradual increase in lake levels. The increasing trend in lake levels is in part driven by a mismatch between Okanagan Lake operations and shifts in inflow timing.

The frequency of declaring drought condition for Okanagan Lake, satisfying either Condition 8bi or 8bii, remains relatively constant at approximately 25% under SSP2-4.5 for both historic and future periods. However, under SSP5-8.5, the frequency of drought declarations is expected to increase from 25% to 32%. Table 4.9 further breaks down the frequency of occurrence by 30-year climatological period. The finer temporal resolution reveals a generally stable trend with time. For the 2071-2100 period under SSP5-8.5, there is a notable increase in the frequency of drought declarations for Okanagan Lake. This increase is primarily driven by larger changes in Condition 8bi at the end of the century but is also associated with high uncertainty. Using a Chi-Square statistical test, the frequency of which the overall drought condition is met for Okanagan Lake is considered statistically similar under SSP2-4.5. Under SSP5-8.5, only the 2071-2100 period is statistically different from all other periods. For context, within the observed record condition 8bi or 8bii have been met 8 times from 1987 to 2024 (21%).

Table 4.9 Percent of years where Condition 8bi or 8bii is met for Okanagan Lake

Period	% Years Condition 8bi or 8bii Met	
	SSP2-4.5	SSP5-8.5
1951-1980	25%	25%
1981-2010	26%	26%
2011-2040	24%	23%
2041-2070	24%	26%
2071-2100	26%	43%

The analysis of the Okanagan drought condition under climate change conditions highlights the importance of Okanagan Lake operations in determining the operations of Osoyoos Lake (i.e. lake levels). It is highly unlikely that operations for Okanagan Lake will remain unchanged until the end of century. Future adjustments to the operation of Okanagan Lake under climate change will impact the operations of Osoyoos Lake and results presented in this study. Close coordination between operational changes for both lakes will be necessary to ensure adaptive and effective water management.

4.2.2 Overall Osoyoos Lake Drought condition

The overall Osoyoos Lake drought condition is declared if either the Similkameen condition (Condition 8a) and Okanagan Lake condition (Condition 8bi or 8bii) is met. Using the updated climate projections (CMIP6 dataset), the Similkameen drought conditions follow a similar trend as those reported in the previous study (NHC, 2021). The percent of years below the 1 million acre-foot drought threshold for Similkameen River near Nighthawk, WA are projected to increase through the end of century. The most substantial change is expected in the 2071-2100 period, particularly for SSP5-8.5, however this is accompanied by high degrees of uncertainty.

The overall drought condition is projected to increase from 15% of the time during the historical period (1950-2019) and increasing to 21% of the time during the future period (2020-2100) under SSP2-4.5. Under SSP5-8.5, this frequency of meeting drought condition increases further to 25% during the future period (2020-2100).

Table 4.10 shows the relative occurrence by 30-year climatological period, which is variable until the end of century, particularly under SSP5-8.5 when the drought condition is met more frequently. Using the Chi-Square test, the 2071-2100 period under SSP2-4.5 is statistically different than the 1951-1980 period. Under SSP5-8.5, the 2071-2100 period is statistically different from all other historical periods.

Table 4.10 Percent of years where Osoyoos Lake Drought condition is met (Condition 8a and Condition 8bi or Condition 8bii)

Period	% Years Osoyoos Drought condition Met	
	SSP2-4.5	SSP5-8.5
1951-1980	13%	13%
1981-2010	16%	16%
2011-2040	18%	15%
2041-2070	20%	23%
2071-2100	23%	37%

4.2.3 Osoyoos Lake Levels

Using the climate change simulations, the frequency of Osoyoos Lake levels exceeding the upper operational range, the timing of peak lake levels, and the frequency of lake levels below the lower operational range were assessed. Additionally, the distribution of April to July inflows and lake levels were assessed to determine if there are statistically significant changes with time.

4.2.3.1 Osoyoos Lake Levels Exceeding the Upper Operation Threshold

To understand changes at the upper operation threshold, the frequency that lake levels exceed the maximum operation lake level condition were estimated. For the purposes of the analysis, high lake level events were separated by periods of minimum 30 consecutive days below the maximum operation lake level. The lake level exceeded the maximum operation level on average 36 times during the historic period (1950-2019) and decreased to 32 times during the future period (2020-2100) under SSP2-4.5. Under SSP5-8.5, the frequency of exceedance decreases further averaging 26 occurrences. Table 4.11 summarizes the frequency that the maximum operation lake level is exceeded by 30 year climatological periods.

Table 4.11 Average number of events exceeding the maximum operation lake level

Period	Average number of events exceeding max operation lake level	
	SSP2-4.5	SSP5-8.5
1951-1980	17	16
1981-2010	15	15
2011-2040	14	14
2041-2070	13	10
2071-2100	9	6

In general, the frequency of Osoyoos Lake level exceeding the maximum operation lake level demonstrates a decreasing trend. This decline is likely driven by the decrease in freshet magnitude of the Similkameen River, leading to a lower likelihood of backwater and backflow conditions in the Okanogan River and Osoyoos Lake.

The duration of the events when lake levels exceed the maximum operation lake level generally remain the same from 1981-2010 through to 2041-2070 and decrease at the end of century (2071-2100) period, as shown in Table 4.12.

Table 4.12 Duration of events (days) exceeding the maximum operation lake level

Period	SSP2-4.5			SSP5-8.5		
	Average (days)	Min (Days)	Max (Days)	Average (days)	Min (Days)	Max (Days)
1951-1980	17	1	54	17	1	49
1981-2010	18	1	64	18	1	64
2011-2040	18	1	62	20	1	54
2041-2070	19	1	60	20	1	59

Period	SSP2-4.5			SSP5-8.5		
	Average (days)	Min (Days)	Max (Days)	Average (days)	Min (Days)	Max (Days)
2071-2100	14	1	46	9	1	48

4.2.3.2 Timing of Osoyoos Lake Peak Levels

The timing of maximum lake level also appears to shift earlier, with more events of lake level exceeding the maximum operation levels in May and fewer events in June and July. Figure 4.10 show the probability density of the dates of the annual maxima series for the historic and future periods. Figure 4.11 plots the distribution date of annual maxima series for the five 30-year climatological periods. The shift in timing of the annual maximum is in part constrained by the operations of Osoyoos Lake with maximum levels allowed during May through September.

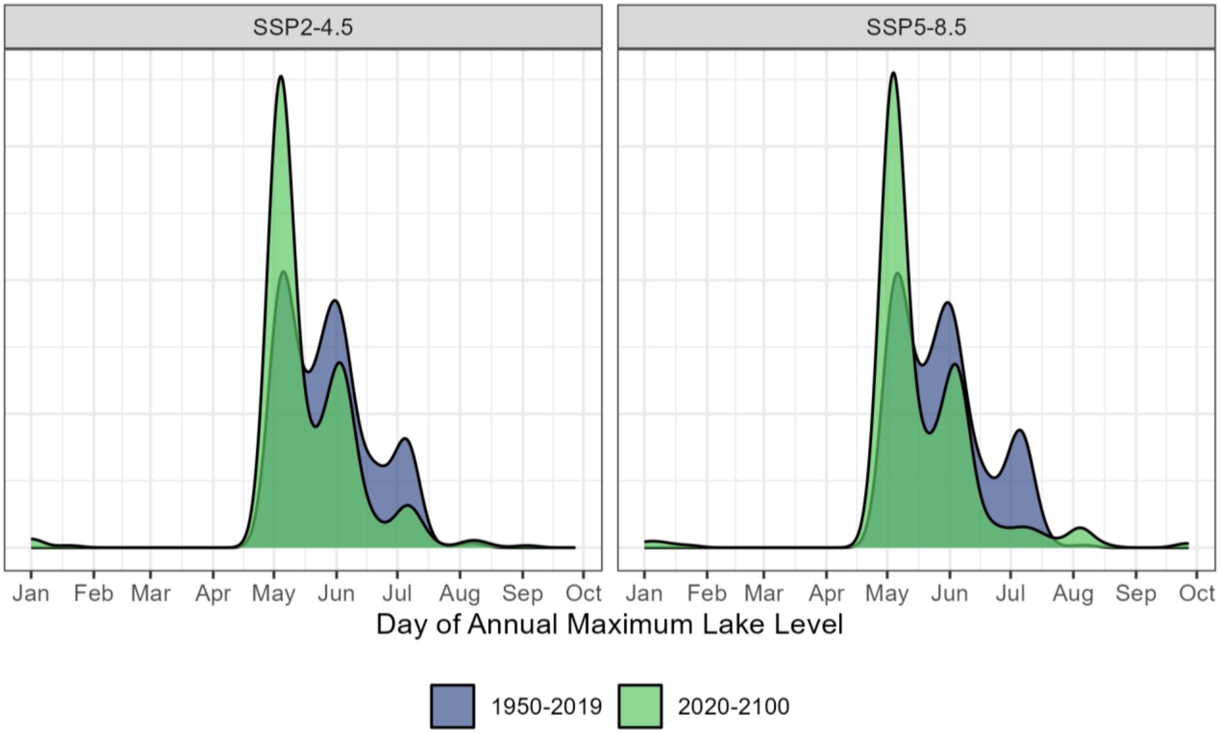

Figure 4.10 Probability distribution of timing of annual maximum Osoyoos Lake levels for the historic period (1950-2019) and future period (2020-2100)

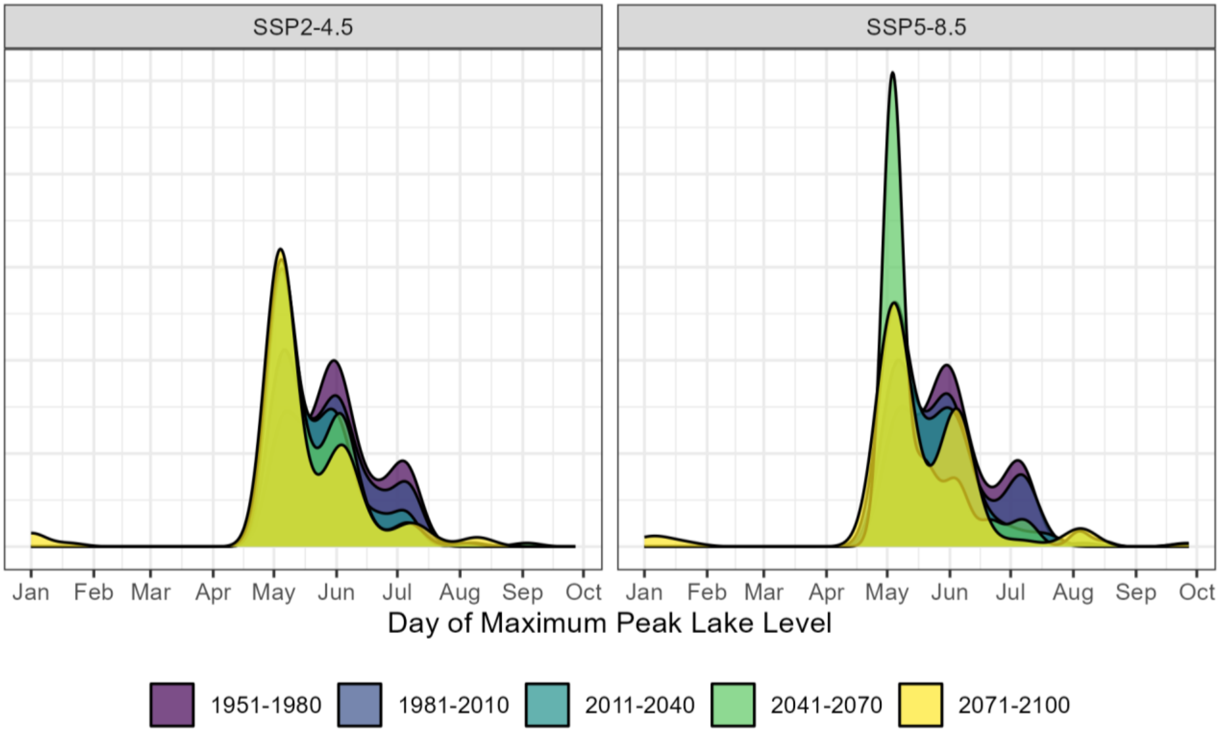

Figure 4.11 Probability distribution of timing of maximum Osoyoos Lake levels for 30-year climatological periods from 1951 to 2100

4.2.3.3 Osoyoos Lake Levels below the Lower Operation Threshold

The frequency of lake levels falling below the lower thresholds of the operation rule curves during the late summer and fall (August to November) were analyzed. The long-term continuous Osoyoos Lake level record was separated to low lake level events (below lower operation thresholds) by 30-day gaps.

Osoyoos Lake levels are below the lower operation threshold on average only once during the historic period (1950-2019). For SSP2-4.5, some GCMs project up to five low lake level events, while the average occurrence across all GCMs is three events. Under SSP5-8.5 the number of times increases to four on average, with up to seven events occurring under some GCMs. When examining the 30-year climatological periods, the lower limit of the rule curve there appears to be no trend with time with one to three events occurring each climatological period for both SSP2-4.5 and SSP5-8.5.

The duration and the deficit of the lower operation thresholds (difference between low lake level and the lower operation threshold) are summarized in Table 4.13 and Table 4.14 for the basic and detailed 30 year periods. Both the duration of the deficit events and the average level below the minimum threshold are expected to increase in the future.

Table 4.13 Summary of duration and deficit below lower operation thresholds for historic and future periods

SSP	Period	Duration (Days)			Depth below lower threshold (m/ft)		
		Average	Min	Max	Average	Min	Max
SSP2-4.5	1950-2019	58	40	67	0.1m/0.33ft	0.02m/0.07ft	0.17m/0.56ft
	2020-2100	70	19	122	0.2m/0.65ft	0.04m/0.13ft	0.59m/1.93ft
SS5-8.5	1950-2019	58	50	65	0.09m/0.3ft	0.02m/0.07ft	0.16m/0.53ft
	2020-2100	75	24	122	0.24m/0.79ft	0.02m/0.05ft	0.54m/1.79ft

Table 4.14 Summary of duration and deficit below lower operation thresholds for 30 year climatological periods

SSP	Period	Duration (Days)			Depth below lower threshold (m/ft)		
		Average	Min	Max	Average	Min	Max
SSP2-4.5	1951-1980	63	61	64	0.13m/0.43ft	0.09m/0.3ft	0.17m/0.56ft
	1981-2010	57	40	67	0.09m/0.31ft	0.02m/0.07ft	0.14m/0.46ft
	2011-2040	85	65	122	0.29m/0.94ft	0.16m/0.52ft	0.52m/1.72ft
	2041-2070	58	19	92	0.13m/0.43ft	0.04m/0.13ft	0.38m/1.23ft
	2071-2100	80	67	92	0.31m/1.03ft	0.13m/0.43ft	0.59m/1.93ft
SS5-8.5	1951-1980	57	50	63	0.09m/0.3ft	0.06m/0.18ft	0.16m/0.53ft
	1981-2010	59	52	65	0.09m/0.28ft	0.02m/0.07ft	0.15m/0.51ft
	2011-2040	80	24	122	0.27m/0.88ft	0.02m/0.05ft	0.54m/1.79ft
	2041-2070	71	56	83	0.19m/0.62ft	0.09m/0.29ft	0.28m/0.92ft
	2071-2100	76	46	92	0.27m/0.89ft	0.14m/0.47ft	0.4m/1.33ft

The frequency, duration, and magnitude of low lake level events where Osoyoos Lake level fall below the lower operation thresholds are dependent on the net inflows to Osoyoos Lake. The net inflows are influenced by both the available water budget in the basin and the operations of the upstream Okanagan Lake and Osoyoos Lake itself, particularly the minimum instream releases. With the increasing trend in Okanagan Lake levels due to changes in Okanagan Lake inflow timing, Okanagan Lake is generally able to maintain present day minimum flow requirements at the Okanagan River at Oliver gauge (08NM085). Adjustments to operations of the Okanagan Lake may be necessary to maintain the Okanagan Lake levels in future climate conditions, which can impact inflows to Osoyoos Lake and alter results from this study.

In drought or low flow conditions of the Osoyoos Lake, adhering minimum instream flow requirements and maintaining a lake level above the lower operation lower thresholds of lake levels can become competing objectives. In the current Raven model, a higher priority was given to maintaining Osoyoos Lake levels above the lower operation thresholds, which means that the instream flow requirements are not always met. This is an area that could be further explored to understand the sensitivity of the lake storage to the instream flow requirements. The current model configuration assumes that all demands are met and does not consider the impacts of limiting demands to help meet the Orders. The model also does not consider the impact of conservation efforts.

4.2.3.4 April to July Lake Levels and Inflows

The distributions of all Osoyoos lake levels for the April to July period were analysed across different time spans using a Wilcoxon rank-sum test to evaluate whether significant differences exist. Using the larger historic and future periods (1950-2019 and 2020-2100) the lake levels during this period are considered to be statistically different. Detailed testing for the 30-year climatological periods indicate that lake levels are considered statistically different from the previous period.

Inflows to Osoyoos Lake during April to July were analyzed to understand whether they differ statistically between the historical (1950–2019) and future (2020–2100) periods. A Wilcoxon rank test was conducted, indicating that inflows in the future period are statistically significantly different from those in the historical period.

5 CONCLUSIONS

Climate change is projected to change the hydrologic response of both the Similkameen and Okanagan basins, ultimately resulting in changes to the frequency in drought conditions and lake levels for Osoyoos Lake.

In both the Similkameen and Okanagan basins, the freshet response is expected to shift earlier with lower freshet peaks because of less precipitation falling as snow during the winter months. Flows during the summer months are expected to decrease but increase again during the fall and winter months due to increased rainfall.

This shift in hydrologic response results in an increase in the frequency in which Drought Condition 8a for Osoyoos Lake is met (Similkameen freshet volume). The frequency of meeting Drought Condition 8bi is also expected to increase (Okanagan Lake inflow). The frequency of meeting Drought Condition 8bii (Okanagan Lake levels) is expected to decrease because of higher lake levels that occur due to a disconnect between current Okanagan Lake operations and changes to future inflows. As a result, overall drought conditions for Osoyoos Lake are expected to increase slightly from present day with a statistically significant change projected under SSP5-8.5 for the end century period (2071-2100). The continued use of Okanagan Lake levels as an indicator of drought presents a challenge as it is not only dependent on changing inflows but also on the operation of Okanagan Lake. The elevation of the drought condition may require revision in the future depending on changes to the operation of Okanagan Lake. Alternatively, the IJC may consider redefining the drought conditions to not be dependent on lake levels.

The number of times the upper lake level rule curve for Osoyoos Lake exceeded is expected to decrease in the future, primarily due to the decrease in the magnitude of freshet peaks on the Similkameen causing fewer backflow or backwater events. The timing of peak lake levels is also expected to shift earlier with the earlier timing of the freshet.

The number of times lake levels drop below the lower limit of the rule curve for Osoyoos Lake is expected to increase slightly in the future, with the duration and magnitude of these events increasing. The limited occurrence of these events is likely in part due to the control of inflows to Osoyoos Lake from Okanagan Lake, whereby changes to operation of Okanagan Lake may impact the frequency and magnitude of these events. Furthermore, lake levels are given precedence over instream flow requirements in the Raven model, which results in the lower lake level limit being met, but instream flow requirements not being met.

The distribution of Osoyoos lake levels and inflows during April to July is statistically different when considering wider time periods (1950-2019 versus 2020-2100) and shorter 30 year periods.

5.1 Future Recommendations

Based on the work completed in the Phase 2 study NHC recommends the following for future work to support understanding of climate change impacts and future guidance of operations on Osoyoos Lake:

- Update the upper portion of the Okanagan hydrologic model to the official version 4.0 of Raven and integrate the latest reservoir operations in Raven throughout the model
- Benchmark and evaluate any potential bias in the gridded climate datasets with reference to the observed historical gridded dataset as outlined in the climate change data scoping study (NHC, 2024)
- Support ongoing data collection including documentation of operation procedures and records, and streamflow measurements of the connection channel between the Similkameen and Okanogan to better understand how much water is conveyed through this channel
- Explore how current operations do or do not meet instream flow requirements under climate change and how upstream operations may need to change to support instream flow requirements

- Coordinate and work in tandem with other studies that explore climate change impacts and changes to operations of Okanagan Lake as changes upstream will directly impact Osoyoos Lake Orders and operations
  - Evaluate how and if the Okanagan basin drought condition linked to Okanagan Lake levels needs to change
- Evaluate if snowpack continues to be an effective measure of drought or if other indicators can be used
  - Reevaluate if the thresholds and time period related to freshet volume should change in the future
  - As the freshet shifts earlier, consider forecasting drought conditions earlier in the year
- Explore the potential for capturing more storage during the fall and winter months, when rainfall is expected to increase, to offset a smaller freshet volume
- Continue an adaptive management approach to reevaluate the effectiveness and understanding of climate change impacts on the Orders as the science and understanding of climate change impacts continues to progress

While the focus of this work was to understand changes to the drought condition and lake levels, the tools and understanding developed as part of this study has many other applications beyond what was covered in this project alone. This could include present day applications such as real-time forecasting and support for management of lake levels, as well as additional climate change analysis such as understanding future water temperatures or how land use / cover change impacts the hydrologic response of the basin.

6 REFERENCES

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APPENDIX A

HYDRAULIC MODEL DEVELOPMENT

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NHC Reference No. 3007619
March 27, 2025

International Joint Commission – International Osoyoos Lake Board of Control

234 Laurier Ave W. 22nd Floor

Ottawa, ON K1P 6K6

Attention: Martin Suchy, Secretary Canadian Section
Sarah Dunn, Secretary US Section
Via email: Martin.Suchy@ec.gc.ca; sdunn@usgs.gov

Re: Osoyoos Lake Climate Change Vulnerability Phase 2 Study
Hydraulic Modelling Documentation Final Report, Rev. 1

Dear International Osoyoos Lake Board of Control:

International Joint Commission – International Osoyoos Lake Board of Control (IOLBC) retained Northwest Hydraulic Consultants Ltd. (NHC) to assess the vulnerability of Osoyoos Lake to climate change impact.

As part of the assessment, NHC developed a hydraulic model to improve the understanding of backflow and backwater effects of Osoyoos Lake, with the model integrated into hydrological modelling that assessed how changes in climate impact the IJC Orders of Approval for Osoyoos Lake.

The purpose of this report is to provide an overview of the technical aspects of the riverine hydraulic model development.

1 INTRODUCTION

Osoyoos Lake is regulated by the operation of Zosel Dam and affected by several factors, including flow releases from the upstream Okanagan Lake and the flow dynamics at the confluence of the Similkameen River downstream of the dam. NHC developed a hydraulic model to understand the complex hydraulic interactions between the Okanagan River and Similkameen River under varying hydrological conditions, with particular focus on the backflow and backwater effects caused by high flows in the Similkameen River.

This report describes the relevant input data, discusses the development of a numerical model of riverine hydraulics, calibration and validation of the model, summarizes the model performance assessment results, and limitations in the use of the model.

1.1 Assumptions and Limitations

The model developed for this study, is not recommended for informing further engineering design, without further detailed verification by a qualified Professional Engineer. Any future changes in land use and land cover require reassessment and potential redevelopment and calibration of the model. Further evaluation is necessary for detailed design. Potential model users use the model at their own risk.

A one-dimensional (1D) numerical hydraulic model was used to simulate hydraulic behaviour within the channel and floodplain for each of the major water bodies within the study region. The hydraulic riverine model developed for the Osoyoos Lake Region improves the understanding of river hydraulics processes causing backwater and backflow conditions in the Okanogan River. However, like all hydraulic models, it has inherent limitations. While multiple factors affect model performance, the most critical ones, with the greatest impact on accuracy, are outlined below.

- The accuracy of the model is limited by the quality of the DEM generated from the available bathymetric and LiDAR data. The project DEM includes regions of lower quality data which impacts the model's ability to represent hydraulic behaviour at the site.
- The riverine system in the study area exhibits very complex hydraulic behaviour, which is difficult to represent through 1D model geometry and governing equations solved by the software.
- Event-based calibration is inherently limited for capturing complex hydraulic phenomena with lag effects. However, long-term simulation is not feasible due to constraints in both available operational records and computational demands.
- Calibration and validation data were limited, with the only relevant observed data available from the Okanogan River at Oroville, WA (USGS 12439500). These two events highlight the challenges posed by the limited spatial distribution of calibration data. While data is available at key locations, these areas are influenced by multiple interacting factors, and there is insufficient data to verify conditions at locations where critical factors exert system-wide impact.
- The model is fixed-bed and stationary, representing only current conditions. During high-flow events and over time, factors such as channel geometry may change, introducing non-stationarity that can affect the model's suitability for simulating future events.
- Further refinements, particularly with expanded observed data, are needed to enhance the 1D hydraulic model's predictive capabilities for future events.

The following sections further explores these limitations through the discussion on model development, input data, calibration process.

2 HYDROLOGIC DATA SOURCES

The details of the multiple gauges near the study region are summarized within Table 2.1. Flow and level data available at these gauges were used for model development, calibration and validation.

Table 2.1 Gauges within the study region.

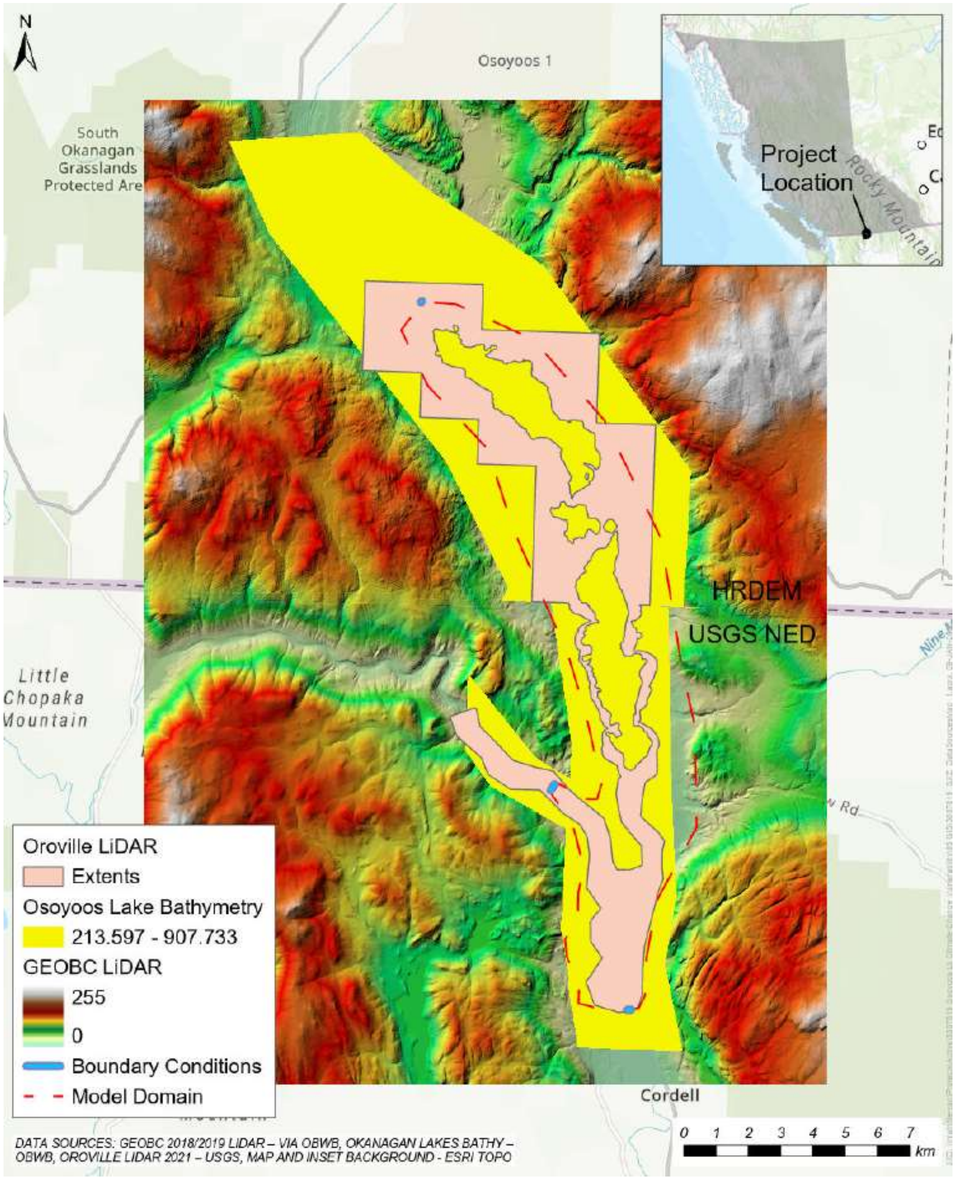
Gauge ID	Name	Location	Owner	Period of Record
08NM085	Okanagan River near Oliver	Okanagan River upstream of Osoyoos Lake	WSC	1944-2024
12439000	Osoyoos Lake Near Oroville, WA	Osoyoos Lake	USGS	2007-10-01 to 2024-07-30
12439500	Okanogan River at Oroville, WA	Okanogan River downstream of Zosel Dam and the railway bridge	USGS	1987-12-28 to 2024-07-30
12442500	Similkameen River Near Nighthawk, WA	Similkameen River upstream of the model boundary condition	USGS	1988-05-01 to 2024-07-30

3 GEOMETRIC DATA SOURCES

This section of the report presents the study area, the coordinate system and sources of geometric data used within this study.

3.1 Model Domain

The upstream and downstream extents of the riverine study (Figure 3.1) were extended sufficiently beyond the study area to prevent any influence on critical result locations and ensure accurate simulation of hydraulic processes within the system. The downstream boundary was set upstream of areas where the DEM data became inadequate, ensuring consistent topographic quality throughout the model and preventing any impact on the results.



DATA SOURCES: GEOBC 2018/2019 LIDAR – VIA OBWB, OKANAGAN LAKES BATHY – OBWB, OROVILLE LIDAR 2021 – USGS, MAP AND INSET BACKGROUND - ESRI TOPO

Figure 3.1 Study area and spatial data sources overview.

3.2 Datum and Projection Coordinate System

The Canadian survey and cartography industry has adopted the Canadian Geographic Vertical Datum 2013 (CGVD2013), and the province of British Columbia is migrating to this datum. As such, CGVD2013 was selected for the project's vertical datum. Results are reported in imperial units and in the NGVD1929 datum where required for consistency with the main report.

The coordinate system details for this model are as follows:

- Horizontal Datum: North American Datum 83 (NAD83) CSRS 3.0.0.BC.1.NVI

- Projection: UTM Zone 11 North
- Vertical Datum: CGVD2013
- Geoid Model: CGG2013a

3.3 Digital Elevation Model

A digital elevation model (DEM) of the terrain was constructed with 1 m resolution using the data presented in Table 3.1 and Figure 3.1. The DEM was generated using the 2018/2019 GEOBC LiDAR as the base topography, supplemented by Okanagan Lakes bathymetric data (surveyed in 1981) and superseded by the 2021 Oroville LiDAR. Intersections between the LiDAR datasets were reviewed for consistency to ensure seamless integration of the surfaces.

Table 3.1 DEM Source Data

Data	Year	Source
LiDAR as the base topography	2018/2019	GEOBC
Okanagan Lakes bathymetric data	Osoyoos Lake surveyed in 1981 and reprocessed in 2019 by NHC	BC Ministry of Environment
Oroville LiDAR	2021	USGS

There are notable uncertainties in the available DEMs that affect the hydraulic model accuracy. During the quality review, some key issues were identified:

- Discrepancies in ground surface elevations among data sources;
- Vegetation data points were not accurately removed from LiDAR data sources, LiDAR data were reprocessed in certain areas before adopted for DEM building; and
- Elevation data accuracy and coverage were poor particularly along river banks.

Corrections were made to improve the issues above, however, such corrections inherit uncertainties from the initial data sources. The overall DEM accuracy was deemed suitable for 1D modeling but may require enhancements for 2D modeling, where higher data resolution and accuracy are needed especially in the channels.

3.4 Hydraulic Structure Data

There are several hydraulic structures within the study area (Figure 3.2). This section describes the structures included in the hydraulic model.

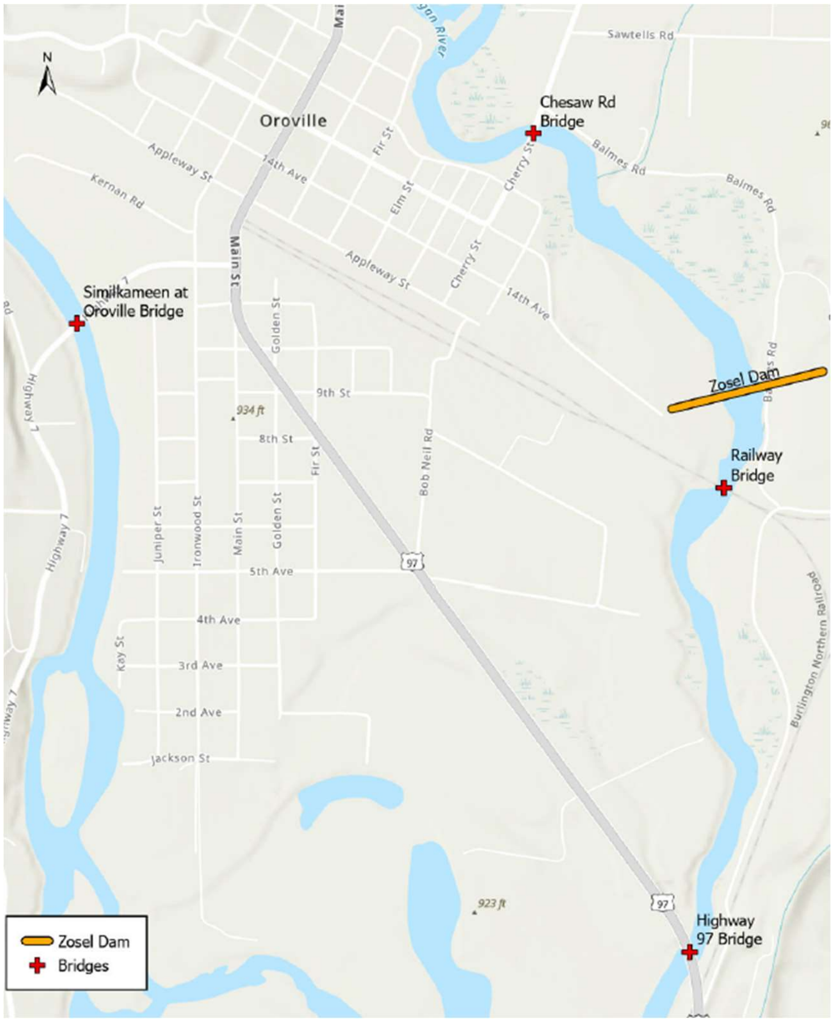


Figure 3.2 Hydraulic structure locations.

3.4.1 Bridge Structures

Four bridges (represented as red crosses in Figure 3.2) are represented within the model domain and modelled with 1D bridge routines in HEC RAS. These bridges are owned by the Washington State Department of Transportation (WSDOT), Okanogan County, and Genesee & Wyoming Railroad Services (GWRR). The hydraulic structure geometries were represented in the model based on the available record drawings listed in Table 3.2.

Table 3.2 Sources of Bridge Record Drawings

Bridge	Structure Owner	Available Drawing Name	Year	Author
Similkameen at Oroville Bridge	Okanogan County	Primary State Highway No. 10 – Similkameen River Bridge, Okanogan County (As-built drawings)	1949	State of Washington – Department of Highways
Chesaw Rd Bridge	Okanogan County	Okanogan County, Washington – Oroville Bridge. Oroville – Toroda Creek Road No. 9480 (As-built drawings)	1970	W. W. WYATT
Highway 97 Bridge	WSDOT	Progress & Final Estimate Profile Primary State Highway No. 10 Oroville South Okanogan River Bridge (As-built drawings)	1951	State of Washington – Department of Highways
Railway Bridge	GWRR	Not available.	Not available.	Not available.

The Chesaw Road Bridge drawings did not have datum information identified, so the elevation of key features was assumed based on the elevation of the approaching road deck in the DEM. Since record drawings were unavailable for the Railway Bridge, orthophotos were used to determine the bridge structure geometries (such as the number of piers, and approximate deck depth). The bridge deck's high chord elevation was estimated from the elevation of the approaching roads on the DEM and the low cord elevation was assumed to be 1m below the high cord.

If the missing data resulted in a bridge simulated too low in the channel compared to existing conditions, the modelled flow would be unnecessarily constricted at those points. Conversely, if the bridge was represented too high above the riverbed, the model would underestimate flow constriction.

3.4.2 Zosel Dam

Outflows from Osoyoos Lake are predominantly regulated by Zosel Dam, which features four independently operated sluice gates, each measuring 25 feet (7.6 m) wide by 12 feet (3.66 m) high, with an invert elevation of 906.0 feet NGVD29 (Acres International Limited, 1987). The dam also includes two fish passageways, each 8 feet (2.4 m) wide and 73 feet (22.3 m) long, located on either side of the spillway. Outflow regulation is primarily managed through the sluice gates, while the fish passageways are assumed to remain open. Additionally, the dam is equipped with a concrete spillway with a crest elevation of 913 feet NGVD29 (278.3 m CGVD2013), providing an emergency spill capacity during high lake level conditions.

Zosel Dam operations impact the hydraulics of the riverine system through disturbance of the Okanogan River flow. As the invert elevations of the dam gates and weir control the flow released through the structure, any differences between modelled and existing conditions may potentially introduce inaccuracies in the model results.

4 HISTORICAL FLOOD DATA

4.1 Overview of Historical Flood Events

The timing of floods from the Similkameen River does not always coincide with flooding conditions on the Okanogan River or Osoyoos Lake. Additional information on the region's hydrology is presented in the companion report (NHC, 2025).

Figure 4.1 provides an overview of the concurrent flow and lake level records from the Similkameen River, Okanagan River, and Osoyoos Lake. The events circled in red below (2018, 2020 and 2021) are those used for model calibration and validation, as described in Section 4.2.

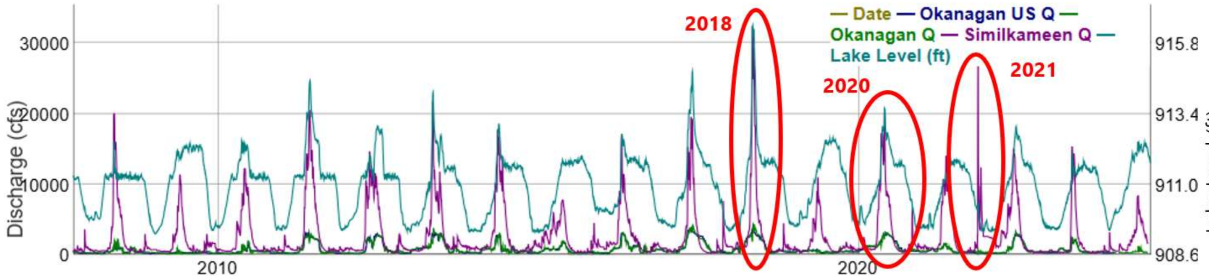


Figure 4.1 Concurrent flow and lake level records used in model development

4.2 Flood Events for Model Calibration and Validation

In scenarios where hydraulic conditions are complex and antecedent conditions play a critical role—such as lake operations influenced by both long-term and short-term forecasting, event timing, and the synchronization of peak flows from the Okanogan and Similkameen Rivers—long-term simulation is essential for accurate calibration. However, long-term simulation was constrained by the model's runtime limitations and the absence of long-term operational records, so alternatively, an event-based approach was used for model development.

Since the primary objective of this model is to simulate backwater and backflow conditions, high flow events in the Similkameen River were selected for event-based calibration and validation. These events were chosen to represent diverse hydrograph shapes and other key variabilities, allowing the model's performance to be assessed across a broad range of hydrological conditions. While an event-based approach has inherent limitations, it is necessary given the substantial data and effort required for more extensive calibration and validation of long-term simulations.

Previous analyses indicate that Similkameen River flows exceeding 10,000 ft^3/s (283 m^3/s) may trigger backwater conditions at Zosel Dam, while flows reaching 20,000 ft^3/s (566 m^3/s) can result in reverse flow at the dam (IOLBC, 2000). However, these threshold conditions can vary depending on the concurrent flow in the Okanagan River. Higher Okanagan River flows may intensify backwater effects but mitigate the extent of reverse flow.

The three most recent high flow events in the Similkameen River were selected for calibration and validation (Table 4.1). The 2018 and 2020 events featured relatively high Okanagan River flows paired with high Similkameen River flows, while the 2021 fall event presented a contrasting scenario with low Okanagan River flow coinciding with high Similkameen River flow.

Table 4.1 Summary of calibration/validation events.

Event	Approx. Return Period		Peak Similkameen Flow	Coincidental Okanagan Flow	Use	Targeted Hydraulic Condition	Zosel Dam Operation
	Similkameen River[1]	Okanagan River[2]	(ft^3/s)	(ft^3/s)			
2018 May Freshet	20-50 year	< 2-year	32,300	3600	Calibration	Backflow	All gates open
2020 June Freshet	2-5 year	< 2-year	20,700	2900	Validation	Backwater	All gates open
2021 November Fall	10-20 year	< 2-year	26,900	240	Calibration	Backflow	Only one gate 0.5-18% open

1. *Bulletin 2020-1-RFFA: British Columbia Extreme Flood Project, Regional Flood Frequency Analysis* (NHC, 2021)
2. *Okanagan Mainstem Floodplain Mapping Project* (NHC, 2020)

There are no surveyed high water marks but two USGS gauges were available as sources of calibration/validation data. For the calibration and validation events, simulated water levels and flows were compared to records on Okanagan River downstream of Zosel Dam at USGS gage: Okanogan River at Oroville, WA (12439500), and simulated lake levels were compared to records at USGS gage: Osoyoos Lake (12439000).

5 HYDRAULIC MODEL DEVELOPMENT

This section describes the key components of the hydraulic model and the rationale for important model assumptions.

5.1 Model Selection

HEC-RAS (Hydrologic Engineering Center - River Analysis System), a computer program developed by the U.S. Army Corps of Engineers' Hydrologic Engineering Center (USACE), was used to develop the hydraulic models for the riverine system in the study area. Version 6.5, released in June of 2023, was used for this study. The program is designed to calculate 1D, 2D, or combined 1D/2D hydraulic calculations for channel networks.

Considering the DEM data available and the proposed model applications, a one-dimensional (1D) hydraulic model was developed for the project model. The benefit of faster simulation runtime was prioritized as long-term simulations were initially considered for project execution. A preliminary 2D hydraulic model was developed to guide the cross-section layout and develop the model geometry.

5.2 Model Configuration

The 1D model (Figure 5.1) includes the Okanogan and Similkameen Rivers, Osoyoos Lake, Zosel Dam, various bridges and connecting structures. An elevation-volume rating curve was used to simplify hydraulic calculations for Osoyoos Lake.

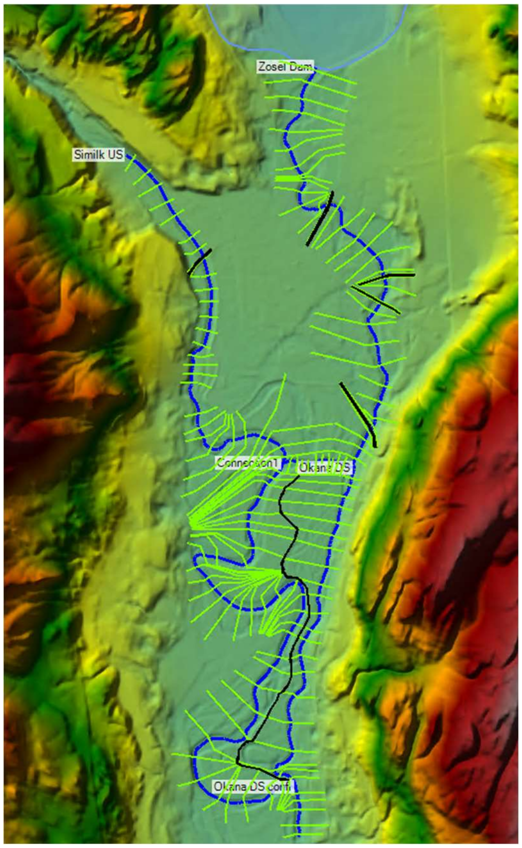


Figure 5.1 Model geometry overview.

The 1D model encompasses three rivers: the Similkameen River, the Okanogan River, and the connection channel upstream of Driscoll Island, which facilitates the majority of flow exchange between the two rivers. The cross-sectional geometry was defined using DEM data, with inherent uncertainties associated with the dataset. Additional uncertainty in the model corresponds to the lack of available flow data for calibration in the connection channel, making it challenging to accurately represent the division of flow between the rivers during modelled events.

Flow exchanges can occur on Driscoll Island through the shared floodplain of the Similkameen and Okanogan Rivers, which becomes inundated during high flows. In the 1D model, this overland exchange was represented with a 2D connection, allowing overland flow to move in and out of Okanogan River depending on the hydraulic conditions. Model simulations of large events of the Similkameen River indicate that only a small portion of the Similkameen River flow enters the Okanogan River over Driscoll Island, with minimal impact on hydraulics upstream of the connection channel.

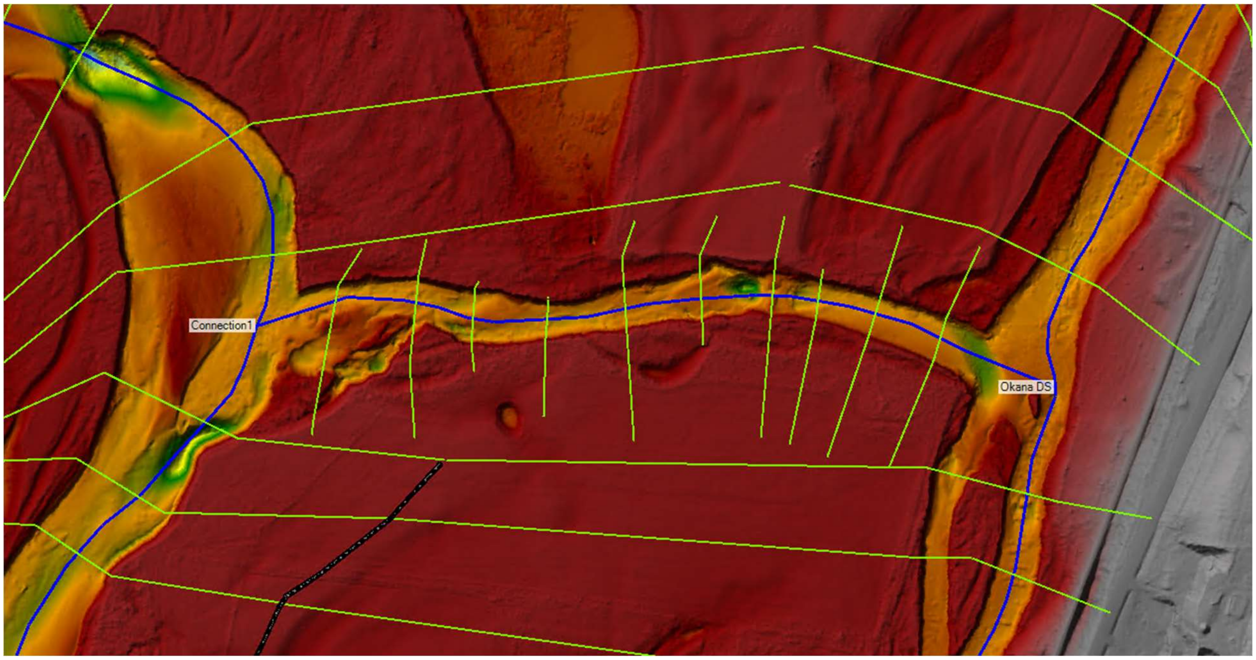


Figure 5.2 Connection channel upstream of Driscoll Island

5.3 Boundary Conditions

The model boundaries (Table 5.1) extend beyond the extent of the locations of interest. This is generally necessary to limit the influence of model boundaries on the model results. Model boundary conditions include inflow entering the upstream end of the model and the normal depth at the downstream end. The boundaries of the models are shown in Table 5.1.

Table 5.1 Boundary Conditions

Location	Boundary Condition Type	Data Source
Similkameen River Upstream	Inflow hydrograph	USGS Gauge 12442500 Similkameen River Near Nighthawk, WA
Osoyoos Lake Upstream	Inflow hydrograph	WSC Gauge 08MN085 Okanagan River near Oliver
Okanogan River Downstream	Normal Depth	DEM

5.4 Initial Conditions

Specifying initial conditions can help achieve model stability and optimize run times. All models require an initial ‘spin-up’ period to allow stabilization and establish hydraulic conditions at the start of a hydrograph, rather than beginning with a dry mesh. Therefore, the results in the “spin-up” phase can be less reliable. For all simulations, the model was given sufficient time to “spin-up” before simulating the period of interest.

5.5 Manning’s Roughness Coefficients

The resistance to flow is defined in the model through hydraulic roughness coefficients. In HEC-RAS 1D models, this is represented using Manning’s roughness coefficient n values. Roughness coefficients account for friction losses resulting from surface roughness, cross-sectional and planform variability, vegetation, and obstructions (i.e., stumps, roots, logs, isolated boulders, embankments, or structures). Where possible the appropriate roughness coefficients should be determined through calibration of the model to observed data.

Due to a general lack of observed data on the floodplain, Manning’s n values of 0.06 was adopted for the floodplains based on technical literature. For the river channels, Manning’s n-values of 0.035 to 0.045 were selected to account for backwater and backflow conditions, representing energy dissipation and momentum exchange effectively during high-flow events. These values were verified or refined through calibration and validation. The coefficients, represented by Manning’s n-values, are the primary variable used to calibrate the model.

5.6 Model Verification

Hydraulic model verification involved developing and testing numerous iterations of the models to ensure that they performed reliably over a range of flows, were numerically stable, and could achieve calibration accuracy targets with reasonable run times. Preliminary sensitivity testing of model timestep, cross section layout, and roughness were performed.

A simplified approach was used to assess the effects of plausible changes in model parameters. It was determined that the model was sensitive to changes in channel roughness, which was the main parameter considered to assess model sensitivity. Although less than the roughness, the model stability and results were also influenced by the computational methods for the connection channel and lateral structure's weir coefficient.

As the bridge low chords tended to be above the simulated water level, the model results generally did not appear to be sensitive to the bridge parameters. Following the verification phase, model calibration and validation were carried out.

6 RIVER MODEL CALIBRATION AND VALIDATION

Calibration and validation of hydraulic models are crucial steps to establishing confidence in the ability of a model to reliably and accurately simulate a range of flow conditions. Calibration involves the refinement of model parameters within physically plausible limits to best match simulated results to those observed in the field for one or more events.

One common challenge in numerical model calibration, regardless of dimension or scale, is that model parameters cannot always account for all hydraulic conditions. This is because the number of factors contributing to complex hydraulic phenomena exceeds the available parameters for calibration. As a result, most models are calibrated to specific conditions that align with their intended future use. In this case, the calibration focused on a combination of Similkameen flows, Okanogan flows, and Osoyoos Lake levels that produce backwater and backflow conditions, particularly when these phenomena cause Osoyoos Lake levels to exceed the normal operating range.

During the model verification process, various input parameters (e.g., hydraulic losses at bridges and dam, cross-section geometry representation, initial conditions, etc.) were tested to assess their impact on model results. Before calibration, key inputs and parameters were adjusted to best represent physical processes and conditions. During calibration, some parameters and inputs were further refined iteratively alongside varying Manning's roughness coefficients. Channel roughness remained the primary parameter for fine-tuning the model to accurately reproduce three backflow and backwater events observed in recent years (see Section 4.2).

The channel's Manning's roughness coefficients did not vary with flow conditions (e.g., depth) and were applied consistently for the entire simulated hydrograph. This uniform application posed a challenge for simulating the entire hydrograph. Higher roughness coefficient values were necessary for simulating high-flow conditions where backwater and back flow effects dominate, and increased resistance was critical to capture energy dissipation through processes cannot be directly simulated by the 1D model (e.g., turbulent mixing, eddies). Such high roughness values may not be appropriate for low and normal flow conditions during the same event.

The calibration process relied on flow and level records records on Okanagan River downstream of Zosel Dam at USGS gage: Okanogan River at Oroville, WA (12439500), and lake levels at USGS gage: Osoyoos Lake (12439000). Although both stations have long and reliable records, they cover only a small portion of the model domain. Since backflow and backwater effects are influenced by the hydraulics of the broader system, this limited coverage makes the calibration process more challenging. Additionally, different combinations of variables can produce similar outcomes. Without calibration data to constrain other critical variables, such as flow through the connection channel or water levels at its confluence points, event-based calibration may successfully reproduce certain events while failing to accurately calibrate others driven by different processes.

The calibration and validation outcomes are presented in Section 6.1 and 6.2, based on these outcomes, a recommended application is summarized in Section 6.3.

6.1 Model Calibration Results

The calibration events were chosen based on higher flows and recency, for the limited calibration gauge data available. Given the complexity of the riverine system, the events were chosen to include situations where backflow or backwatering was experienced at Zosel Dam. Details of the available calibration data are listed in Table 6.1.

Table 6.1 Calibration event data.

Calibration Event	Event Dates	Similkameen Peak Flow	Okanogan Peak Flow	Osoyoos Lake Level	Approx. Return Period		Available Data
					Similkameen River[1]	Okanagan River[2]	
2018 Freshet	April 15 - June 29	32,000 ft³/s	3641 ft³/s	916.77 ft NGVD29	20-50 year	< 2-year	USGS gauge water level and flow data at 12439500 and gauge water level at 12439000 (2 points).
2021 Fall	Nov 15 – Nov 23	26,900 ft³/s	230 ft³/s	910.87 ft NGVD29	10-20 year	< 2-year	USGS gauge water level and flow data at 12439500 and gauge water level at 12439000 (2 points).

1. *Bulletin 2020-1-RFFA: British Columbia Extreme Flood Project, Regional Flood Frequency Analysis* (NHC, 2021)
2. *Okanagan Mainstem Floodplain Mapping Project* (NHC, 2020)

The roughness coefficient was increased in the upstream channel portion of the Similkameen River. The roughness coefficient was varied on the Okanogan River downstream of Zosel Dam to better represent the hydraulic behaviours indicated in the calibration data. The Okanogan River calibrated well to the 2018 freshet and 2021 fall event, as shown in a summary of the peak flow and water level for the events at USGS gauges 12439500 *Okanogan River at Oroville, WA* and 12439000 *Osoyoos Lake Near Oroville, WA* in Table 6.2.

Table 6.2 Calibration results summary.

Calibration Event	Okanogan River Peak Flow (ft^3/s)		Okanogan River Peak Water Level (ft NGVD29)		Osoyoos Lake Peak Water Level (ft NGVD29)	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
2018 Freshet	4295.01	3653.41	916.18	915.03	916.42	916.06
2021 Fall	618.50	466.26	913.63	912.78	910.36	910.43

The time series of the flow and water level during the flood events were extracted from the gauge and the model, as shown in Figure 6.1 and Figure 6.2. The simulated water levels best match the gauge data during the peak of the 2021 fall event. Lower flows are simulated at the Okanogan River gauge location upstream of the connection compared to what was observed by the gauge, indicating that less backflow is being simulated in the model.

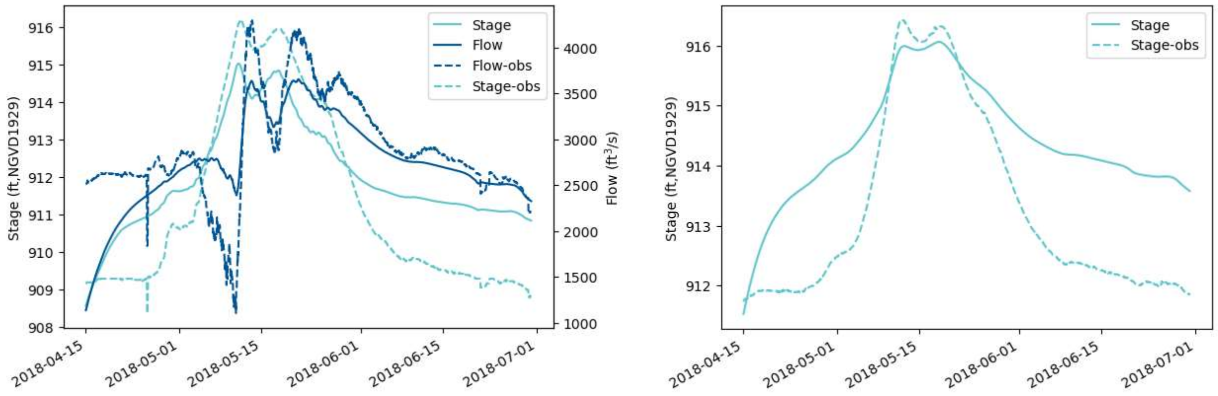


Figure 6.1 2018 Freshet Calibration Results (left: Okanogan River, right: Osoyoos Lake).

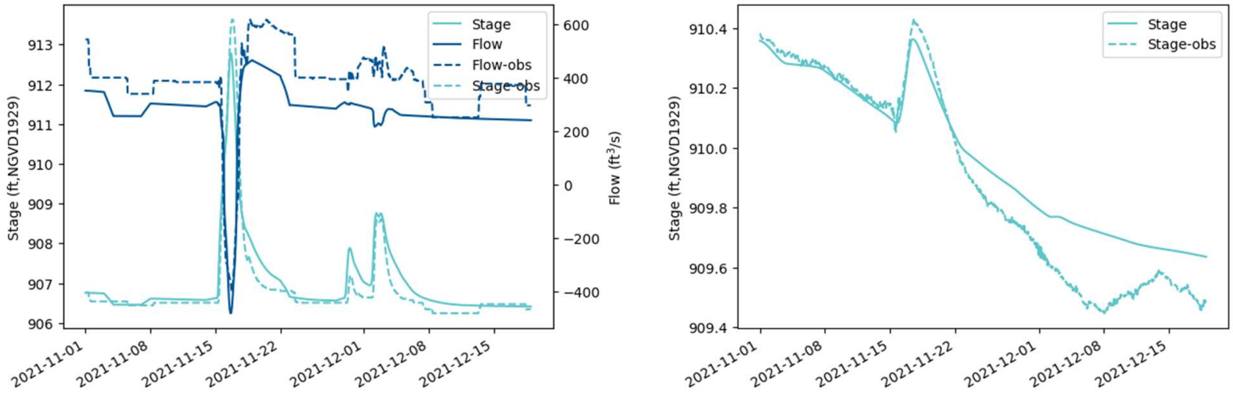


Figure 6.2 2021 Fall Calibration Results (left: Okanogan River, right: Osoyoos Lake).

6.2 Model Validation Results

After the model was successfully calibrated, it was validated with another flood event. The purpose of model validation is to confirm that the calibrated model performs reliably for one or more flood events other than the calibration event. The level of agreement between model results and observational data from validation runs builds an understanding of model confidence, or conversely uncertainty. With good agreement, the confidence in the model is increased, with the expectation that it performs well for flood events.

The model was validated with the 2020 freshet flood. As with the calibration events, the only available data are from the USGS gauges. Details of the validation event are summarized in Table 6.3.

Table 6.3 Validation event data.

Validation Event	Event Dates	Similkameen Peak Flow	Okanogan Peak Flow	Osoyoos Lake Level	Approx. Return Period		Available Data
					Similkameen River[1]	Okanagan River[2]	
2020 Freshet	May 1 - July 28	20,700 ft^3/s	2790 ft^3/s	914.15 ft NGVD29	2-5 year	< 2-year	USGS gauge water level and flow data at 12439500 and gauge water level at 12439000 (2 points).

1. *Bulletin 2020-1-RFFA: British Columbia Extreme Flood Project, Regional Flood Frequency Analysis* (NHC, 2021)
2. *Okanagan Mainstem Floodplain Mapping Project* (NHC, 2020)

The Okanogan River validated well to the 2020 freshet event, as shown in a summary of the peak flow and water level for the events at USGS gauges 12439500 *Okanogan River at Oroville, WA* and 12439000 *Osoyoos Lake Near Oroville, WA* in Table 6.4.

Table 6.4 Validation results summary.

Calibration Event	Okanogan River Peak Flow (ft³/s)		Okanogan River Peak Water Level (ft NGVD29)		Osoyoos Lake Peak Water Level (ft NGVD29)	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
2020 Freshet	3227.50	2969.02	913.26	912.96	913.65	915.06

The time series of the flow and water level during the flood was extracted from the gauge and the model, as shown in Figure 6.3.

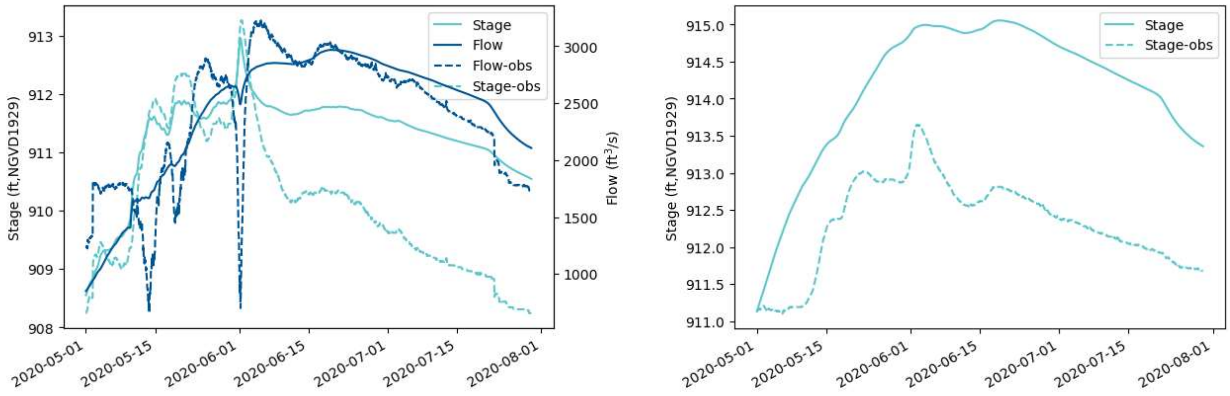


Figure 6.3 2020 Freshet Calibration Results (left: Okanogan River, right: Osoyoos Lake).

6.3 Summary and Recommended Application

The calibration of the 2018 event and the validation of the 2020 event represent high-flow conditions in both the Similkameen and Okanogan Rivers during the freshet season. For both events, the calibration shows a good match for water levels at the Okanogan River downstream of Zosel Dam (USGS 12439500), with a slight underprediction compared to observed values. However, the model underestimates the backflow effect, leading to an overestimation of Okanogan River flow during these conditions. Given the cross-sectional geometry at this location, the stage difference between the simulated and observed values alone cannot fully account for this flow discrepancy.

Under normal flow conditions, flow scales predictably with stage; however, the model's underprediction of water levels while simultaneously overpredicting flow suggests limitations in the 1D shallow water equations solved by HEC-RAS. This numerical limitation likely contributes to the model's poor performance in replicating Osoyoos Lake levels (USGS 12439000). Additionally, inaccuracies in the digital elevation model (DEM) of the side channels and wetlands between Zosel Dam and the lake outlet may further contribute to spatial calibration discrepancies.

These two events highlight the challenges posed by the limited spatial distribution of calibration data. While calibration data is available at key locations, these areas are influenced by multiple interacting factors, and there is insufficient data to verify conditions at locations where critical factors exert system-wide impacts. The 2018 calibration, in particular, indicates that the model underestimates backflow effects when Okanogan River flows exceed a certain threshold.

In contrast, the 2021 fall flood event in the Similkameen River occurred alongside very low flows from the Okanogan River. During this event, backflow was strictly regulated at Zosel Dam, with only one gate open for most of the event. The model successfully replicated these conditions, underscoring the importance of concurrent Okanogan River flow (or antecedent lake level) in influencing backflow dynamics alongside Similkameen River conditions.

Based on these results, we conclude that the model is a valuable tool for simulating physical processes and understanding the causes and likely impacts of backflow events. However, further calibration efforts are hindered by data limitations. While parameters can be adjusted further, the degree of freedom in parameter selection is too high relative to the number of locations where these variables can be constrained using available calibration data. As a result, while the identified threshold conditions provide useful insights, they may require further refinement with improved spatial data coverage and additional calibration points.

Backflow Triggers: Backflow events can occur under various combinations of Similkameen and Okanogan River flows, and their impact on Osoyoos Lake levels is highly variable.

Thresholds for Backflow: Backflow has been observed when Similkameen River flows exceed 15,000 ft^3/s (509.7 m^3/s) with Okanogan River flows above approximately 2119 ft^3/s (60 m^3/s), such as during the 2020 freshet event. It can also occur when Similkameen flows exceed 20,000 ft^3/s (566.3 m^3/s), regardless of Okanogan River discharge.

Variable Lake Level Response: Backflow events do not always lead to significant lake level rises; their impact depends on factors such as in-channel storage capacity, sluice gate operations at Zosel Dam, and antecedent lake conditions.

Storage and Delay Effects: Some backflow is temporarily stored within the channel, which can delay or dampen its effect on lake levels.

Influence of Okanogan River Flows: Higher concurrent Okanogan River flows can alter backflow dynamics, sometimes reducing reverse flow but also enhancing backwater effects that impede Osoyoos Lake outflows, leading to elevated lake levels.

7 CONCLUSIONS

The 1D hydraulic riverine model developed for the Osoyoos Lake region provides valuable insights into river, lake, and floodplain dynamics. Calibration and validation against high-flow events in 2018 and 2020 demonstrated reasonable agreement with observed water levels but highlight limitations in capturing backwater and backflow effects, likely due to numerical constraints of the 1D modeling approach and data limitations. The model successfully replicated the 2021 fall flood event, underscoring the importance of concurrent Okanogan River flows in backflow dynamics.

While the model effectively simulates key processes, its accuracy is limited by factors such as DEM quality, limited calibration data (spatial distribution), and the complexity of hydraulic interactions. This model was used to aid regression analysis by providing a physical basis for understanding the processes reflected in the correlations of the gaged data.

Further refinements, particularly with expanded observed data, are needed to enhance the 1D hydraulic model's predictive capabilities for future events.

CLOSURE

We trust this report meets your needs and provides the necessary background on hydraulic modeling and its application within the broader project. If you have any questions or requests, please feel free to contact the undersigned.

Sincerely,

Northwest Hydraulic Consultants Ltd.

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EGBC Permit to Practice Number:

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