Okanagan Mainstem Floodplain Mapping

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Photo credits of the 2017 flood, clockwise from top: District of Summerland, District of Lake Country, City of Kelowna (2) - Michael Hintringer.
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FINAL REPORT

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- the Regional Districts of North Okanagan, Central Okanagan, and Okanagan-Similkameen;
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EXECUTIVE SUMMARY

Overview – *a Technical Summary is provided on the following page*

Record-setting high flows and flooding in the Okanagan Valley in 2017, followed by high flows in 2018, prompted the Okanagan Basin Water Board (OBWB), the Okanagan regional districts, member municipalities, and the Okanagan Nation Alliance and member communities to update floodplain mapping for the Okanagan River and its lakes.

Northwest Hydraulic Consultants Ltd. (NHC) was retained by OBWB to develop comprehensive floodplain mapping for:

- the Okanagan River: from Penticton to Osoyoos Lake; and,
- the Okanagan River's mainstem lakes: Ellison/Duck, Wood-Kalamalka, Okanagan, Skaha, Vaseux, and Osoyoos.

To plan for the future and guide development in the floodplain, the recommended floodplain mapping is based on mid-century climate (2041-2070), with maps for long-term planning purposes based on end-of-century climate (2071-2100). It has been assumed that land use change to the mid-century period will be limited to urban development, with logging practices in the Okanagan River Basin similar in scope as over the last 50 years. Thus, land use change is not expected to be substantial enough to impact the results of this study's recommended floodplain mapping and was not considered. However, changes within the basin that were also not considered and have the potential to occur at a larger scale, for example, forest pests, disease, and wildfires, could impact the results of this study. If such larger scale changes occur, the results of this study must be re-assessed.

The project included working with the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD), the operator of the Okanagan Lake Regulation System (OLRS), to develop preliminary modifications to the OLRS Operating Plan and guidelines to mitigate the expectation for higher and more frequent floods in the future. **The floodplain mapping is contingent on such modifications, and without them, the design flood level for Okanagan Lake, for example, would be 0.45 m higher.** These preliminary modifications are an initial step and only consider flood control. Further work is needed to review how this can be balanced with First Nations, fishery, agricultural, and recreational interests since these modifications are in contrast to current fish and water management objectives. Balancing these interests could depend on a significant expansion of the flood conveyance capacity in the Okanagan River down through to Osoyoos Lake. It is recommended that these modifications and options to balance interests be reviewed within the next five years with the Okanagan Nation Alliance and Canadian Okanagan Basin Technical Working Group (COBTWG) and the wider stakeholder group, given the projected rate of change in floods due to a changing climate.

The floodplain maps include flood inundation extents, with and without freeboard, and are provided as map sheets attached to this report. The Flood Construction Level (FCL) is the 'design flood' plus freeboard. These and additional layers have also been provided to OBWB as electronic map files, including flood hazard mapping (showing flood depth and velocity), and mapping for the following 'average recurrence interval' floods: 20-year, 100-year, 200-year, and 500-year.

The Okanagan River dikes generally contain large floods, but flooding is still possible as these dikes could fail through stability and seepage mechanisms and can breach even if not overtopped. Where particular vulnerabilities exist is where the dikes are shown to overtop under the design event and where non-gated culverts would allow back flooding through dikes or embankments during the design event. Guidance on application of the floodplain mapping to reduce flood risk is summarized in this report, including:

- Structural mitigation: flood barriers, flow conveyance improvements, flood flow reduction, erosion protection, and monitoring and maintenance; and
- Non-structural mitigation: land-use management, flood proofing individual assets, flood prediction and warning, flood emergency response planning, community recovery plans, and community awareness.

To raise public awareness, the overall project includes a website with an aim to inform the public on potential flood hazards and to provide useful resources on reducing flood risk. The website includes the electronic floodplain maps from this study. Prior to applying the maps, models, or other findings or results from this study, it is recommended that the entire document be read and understood. We suggest that the reader contact NHC or other Qualified Professional(s) for support on understanding the topics presented.

Technical Summary

Two atypical freshets in 2017 and 2018 prompted OBWB, the Okanagan regional districts, member municipalities, and the Okanagan Nation Alliance and member communities to update floodplain mapping for the Okanagan Valley lakes and the Okanagan River. The 2017 freshet resulted in peak lake levels in Kalamalka and Okanagan lakes that exceeded their previously estimated 200-year average recurrence interval (ARI)[1] levels (from 1991 floodplain mapping), and were the highest levels that have occurred since the dams were built[2]. This record-setting freshet was driven by late season snow accumulation followed by rapid melt and rain. This was then followed by an atypical freshet in 2018, due in part to early freshet rain in the lower valley, which caused Okanagan River flows at Oliver to peak three weeks earlier than the Okanagan Lake level (the Okanagan Lake peak level in 2018 was ~0.57 m lower than the peak in 2017). The maximum daily inflow to Okanagan Lake in 2017 exceeded the last three largest events on record (1948, 1972, and 1997), with the most notable difference being the reduction in time to the peak (21 days versus the range of 31-45 days observed for the other three historical events).

[1] A specified ARI event can occur in any year. The specified event's Annual Exceedance Probability (AEP) = 1/ARI, and its AEP is the same in any year, given: the same type of event is being considered, there is no trend in this event type over time, that the events are independent from year to year, and also random. ARI is also referred to as 'return period', but the term is not used in this study due to its frequent misinterpretation: 'return period' can be misinterpreted to mean that the event only occurs once in the specified period; however, the event can occur in any year.

[2] Associated Environmental Consultants Inc. (2017b). *Review of 2017 Flood Response: Okanagan Lake Regulation System and Nicola Dam, prepared for Ministry of Forests, Lands, Natural Resource Operations & Rural Development*.

NHC's primary objective in this study was to develop comprehensive floodplain mapping for the Okanagan River mainstem lakes and the Okanagan River from Penticton to Osoyoos. The OLRS presents a unique challenge for determining ARI values for floodplain mapping, since it contains a series of regulated lakes managed with various seasonal level and flow guidelines, and management of the flow from the lakes is informed by current conditions and forecasts from the River Forecast Centre (RFC). The flow targets have been carefully developed through the collaborative effort of agencies and First Nations, to balance interests in fisheries, agriculture, flood control, and recreation. An additional objective of this study was to improve the understanding of flood management options available to Okanagan water managers and operators in the face of climate variability and change, and modifications to flood management have been incorporated into the floodplain mapping as detailed further below.

To achieve these two objectives, NHC developed a hydrologic model[1] of the Okanagan River Basin (ORB), which includes an objective representation of OLRS operations using current and preliminary future guidelines, and also current guidance using RFC's existing inflow forecast models. The hydrologic model was first calibrated to unregulated subbasins in the ORB, with OLRS operations and representations of the mainstem dams added to the model to form an operations model. NHC addressed estimation of design lake level and river flow ARIs for floodplain mapping through simulation of a climate ensemble. The hydrologic model was driven with the 50-member climate ensemble[2] representing plausible historical weather (starting in 1950) and how it may have developed to the year 2100[3]. This provided a long-term series of simulated freshets from which the frequency of lake levels and river flows in the system were analyzed, to determine design ARIs for each mainstem lake and the Okanagan River.

To address the second objective of this study, NHC worked with FLNRORD to review projected future climate and associated Okanagan Lake inflows and modify the current OLRS Operating Plan and guidelines[4] to manage future high flows. These modifications are preliminary and based only on flood control, and the results of the mid-century and end-of-century floodplain mapping are contingent on these modifications. The future projections of flood inundation (in particular Okanagan and Wood-Kalamalka lakes) to the mid-century period is dependent on these modifications to better absorb and react to large inflows that might occur earlier in a water year (October-September). Results show that the reservoir inflows are likely to be more difficult to forecast over time due to a decreasing influence of snow accumulation and increasing influence of rain. The modifications to the OLRS Operating Plan and guidelines for Okanagan Lake are:

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[1] Raven Hydrological Modelling Framework, http://raven.uwaterloo.ca/, accessed 31 March 2020.

[2] Each ensemble member was randomly generated by Environment and Climate Change Canada, and then downscaled by NHC.

[3] How climate may develop is based on a projection of global warming (and resulting climate change) following Representative Concentration Pathway 8.5 (RCP8.5). This is a greenhouse gas concentration trajectory, with the '8.5' representing this RCP's net increase of 8.5 W/m^2 (watts per metre squared) in global average radiative forcings at the end of this century (2100).

[4] Associated Environmental Consultants Inc. (2017b). *Review of 2017 Flood Response: Okanagan Lake Regulation System and Nicola Dam, prepared for Ministry of Forests, Lands, Natural Resource Operations & Rural Development*.

- Allowing up to 78 m^3/s outflow from Okanagan Dam at Penticton for the entire period of February through September. In the current Operating plan, this maximum outflow is only allowed from April-July.
- Lowering the target levels on Okanagan Lake by 0.20 m (below present guidelines) for the period of October-March.

We have found that at Okanagan and Kalamalka lakes, the 2017 lake levels were nearly equivalent to the present day 500-year ARI lake levels. Even with modification to the operations, the 500-year ARI Okanagan Lake level increases by 0.39 m from the present day to the mid-century period (2041-2070). Without these changes, the 500-year Okanagan lake level may increase by 0.84 m in mid-century (resulting in design flood levels that would be 0.45 m higher than is incorporated into the floodplain mapping developed in this study), and 1.25 m by the end-of-century (2071-2100). These changes, in particular the increased period for higher outflow rates, are expected to be negative to fish spawning on the Okanagan River without mitigative works downstream of Penticton, and also have the potential to impact aging downstream infrastructure. Review of these preliminary modifications with the Okanagan Nation Alliance and COBTWG and the wider stakeholder group is needed. Preliminary discussions with FLNRORD, OBWB, and NHC on potential mitigative options included further work on reactivation of the Okanagan River floodplain and side channels to improve the conveyance and dissipation of flow in the floodway and fish habitat in the side channels.

Recommendations for design levels have been based on guidelines[1 and others], and following discussions with OBWB and FLNRORD, the mid-century 200-year ARI event was used to define the design flow for Okanagan River and design still-water level for the mainstem lakes. The exception to this was Okanagan and Kalamalka lakes, where the flood of record (2017), adjusted to mid-century climate, was used as the design level. Although not clearly defined by regulation or guideline, the use of the flood-of-record where it exceeds the 200-year ARI, has been applied elsewhere in the province. In the lower Fraser River[2], for example, the flood-of-record (1894) has been used as the design flood and is coincidentally also estimated to have an ARI of 500-years. Of note, is that the mid-century 200-year ARI still-water level for Osoyoos Lake is ~0.19 m higher than the 1894 flood-of-record for the lake, with the 200-year value recommended as the minimum design level.

[1] EGBC (2018). *Legislated Flood Assessments in a Changing Climate in BC, Version 2.1*. Engineers & Geoscientists British Columbia, Burnaby, BC. 192 pp.
APEGBC (2017). *Flood Mapping in BC, APEGBC Professional Practice Guidelines, V1.0*. The Association of Professional Engineers and Geoscientists of British Columbia, Burnaby, BC. 54 pp.
FLNRORD (2018). *Flood Hazard Area Land Use Management Guidelines, originally Ministry of Water, Land and Air Protection, Province of British Columbia, May 2004, amended January 2018 by the Ministry of Forests, Lands, Natural Resource Operations and Rural Development*. Ministry of Forests, Lands, Natural Resource Operations and Rural Development.
MOELP (1999). *Guidelines for Management of Flood Protection Works in British Columbia*. Province of British Columbia, Ministry of Environment, Lands & Parks.

[2] FBC (2016). *Lower Mainland Flood Management Strategy: Phase 1 Summary Report.* Fraser Basin Council.

The effect of waves was simulated on the mainstem lakes using a wave model[1], which uses a spatially-varying wind field and 200-year ARI (seasonal) wind speeds, estimated from observed wind data at Penticton and Kelowna. The wind field was compared to prevalent wind conditions on Okanagan Lake from a past buoy study[2] and found to be in general agreement. Waves reaching the shoreline vary due to the wind field as well as the fetch (distance of water the wind acts on). Furthermore, the runup of the waves vary with a lake's shoreline elevation and slope. Therefore, the wave effects vary around a lake, and each lake required multiple FCL shoreline zones. A total of 22 FCL shoreline zones were determined for all of the mainstem lakes, with Okanagan Lake for example having eight. The FCL shoreline zone where there are wave effects, is based on a combination of: the mid-century still-water level, storm surge (wind setup), wave effects (wave runup), and freeboard (0.6 m). The FCL shoreline zone has a set width of 40 m subject to topographic limits, beyond which the FCL lake zone excludes the wave effect component. The wave runup calculations for the FCL shoreline zone are based on a generalization of bare-earth topography.

The potential for tsunami driven waves in Okanagan Lake was also reviewed, and only two cases of landslide-generated tsunami waves have been documented, with wave heights ranging from 1.5 to 4 meters. The risk of an earthquake-triggered landslide capable of producing tsunami waves in Okanagan Lake is also discussed in this report – it was deemed to be infrequent and not used for the floodplain maps.

The conveyance of flow through the Okanagan River and potentially its floodplain was simulated with a hydraulic model[3] that was developed for the Okanagan River from Penticton to Osoyoos Lake. The model used the recommended design flow ARIs as input (determined from the frequency analysis of the hydrologic model outputs), to estimate depth of water in these areas and the extent of flooding. Dike breaching was considered through a simplistic approach[4], and the hydraulic model was also used to simulate the hazard of flow through the floodplain for the design flood ARI. This generated a spatial grid of both flow depth and velocity to quantify hazard in the floodplain; however, due to the simplistic approach used, the depth and velocity hazards near the main channel may be underestimated.

The above information was used to develop floodplain maps in a Geographic Information System (GIS)[5], with the flood inundation extents, with and without freeboard, provided as map sheets (attached as

[1] SWAN: Simulating WAves Nearshore, Delft University of Technology, https://www.tudelft.nl/en/ceg/about-faculty/departments/hydraulic-engineering/sections/environmental-fluid-mechanics/research/swan/, accessed 31 March 2020.

[2] Spence, C., and Hedstrom, N. (2015). Attributes of Lake Okanagan evaporation and development of a mass transfer model for water management purposes. *Canadian Water Resources Journal / Revue canadienne des ressources hydriques*. doi:10.1080/07011784.2015.1046140.

[3] HEC-RAS: Hydrologic Engineering Center's River Analysis System, United States Army Corps of Engineers, https://www.hec.usace.army.mil/software/hec-ras/, accessed 31 March 2020.

[4] '*Appendix C - Former Non-Accredited Levee System Evaluation and Mapping Approach*' of FEMA (2013). *Analysis and Mapping Procedures for Non-Accredited Levee Systems, New Approach, Federal Emergency Management Agency (FEMA)*.

[5] Esri ArcGIS, https://www.esri.com/en-us/arcgis/about-arcgis/overview, 31 March 2020.

electronic files to this report). These and additional layers noted in the Overview above have also been provided to OBWB in GIS format.

We again encourage that this entire document be read and understood prior to applying the maps, models, or other findings and results from this study, and suggest that the reader contact NHC or other Qualified Professional(s) if support is needed to gain understanding of the topics presented.

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Photo 1-2 Areas immediately west of the Okanagan Lake Dam around the time of the 2017 peak (June 8), clockwise from top-left: looking north at sandbagging along the perimeter of the lake (June 2); same area with increased sandbagging 3 days later (June 5); looking south along the lake shoreline towards Okanagan Dam (June 2); and the Okanagan Lake Dam a month earlier (May 7). The June 2 and 5 average water levels were respectively 83.3 and 0.864 m higher than on May 7; the 2017 instantaneous peak Okanagan Lake water level on June 8 was 0.027 m higher than the June 5 mean water level. Photo credits: Mike Noseworthy, FLNRORD. 1-13

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ABBREVIATIONS

AEP	Annual Exceedance Probability
AET	Actual Evapotranspiration
ARI	Average Recurrence Interval
BC	British Columbia
BC MOE	British Columbia Ministry of Environment
CEM	Coastal Engineering Manual
CGVD28	Canadian Geodetic Vertical Datum of 1928
CGVD2013	Canadian Geodetic Vertical Datum of 2013
CSRS	Canadian Spatial Reference System
DEM	Digital Elevation Model
DFO	Fisheries and Oceans Canada
DSR	Dam Safety Review
ECCC	Environment and Climate Change Canada
EFN	Environmental Flow Needs
FCL	Flood Construction Level
FLNRORD	British Columbia Ministry of Forests, Lands, Natural Resource Operations, and Rural Development
FWMT	Fish and Water Management Tool
GIS	Geographic Information System
HBV	Hydrologiska Byråns Vattenbalansavdelning
HEC-RAS	Hydrologic Engineering Center – River Analysis System
HEC-SSP	Hydrologic Engineering Center – Statistical Software Package
HRU	Hydrological Response Unit
HWM	High Water Mark
IJC	International Joint Commission
Lidar	Light Detection and Ranging
LLO	Low-Level Outlet
MOE	British Columbia Ministry of Environment

NHC	Northwest Hydraulic Consultants Ltd.
NAD83	North American Datum of 1983
NRCan	Natural Resources Canada
NSE	Nash-Sutcliffe efficiency
OBA	Okanagan Basin Agreement
OBHM	Okanagan Basin Hydrologic Model
OBIA	Okanagan Basin Implementation Agreement
OBWAM	Okanagan Basin Water Accounting Model
OBWB	Okanagan Basin Water Board
OHCM	Okanagan Hydrologic Connectivity Model
OLRS	Okanagan Lake Regulation System
ONA	Okanagan Nation Alliance
ORB	Okanagan River Basin
OWDM	Okanagan Water Demand Model
OWSDP	Okanagan Water Supply and Demand Project
PET	Potential Evapotranspiration
RCP8.5	Representative Concentration Pathway 8.5
RDCO	Regional District of Central Okanagan
RFC	River Forecast Centre
RMSE	Root Mean Square Error
SWE	Snow Water Equivalent
TAC	Technical Advisory Committee
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VDS	Vertical Drop Structure
WSC	Water Survey of Canada
WSE	Water Surface Elevation

CHAPTER 1 INTRODUCTION

1.1 Document Guide

This report is arranged by the study's general flow of work:

- Chapter 1 – Introduction:
  - Provides an overview of the study area and the study's main objectives. The reader is advised to review the Project Limitations section in detail. This chapter also provides background to the study, including climate, history of flooding (including 2017 and 2018), OLRS operational challenges, and past relevant studies.
- Chapter 2 – Climatology:
  - Climatology is the study of climate, specifically weather conditions averaged over time. This section reviews historic climate and plausible future climate due to global warming. We discuss how global warming leads to climate change, and review the changes expected in the ORB and also the adjacent Similkameen River basin, as the latter is relevant to backwatering at the confluence of the two to Osoyoos Lake. We describe the datasets and processes undertaken in this study to develop a climate dataset that is suitable for driving a model of the ORB hydrology, described briefly below.
- Chapter 3 – Hydrology:
  - Hydrology is the study of a planet's water cycle, the distribution, movement, properties, and exchange of water in the atmosphere and on the surface and subsurface. This section discusses the development of a model, used to simulate the hydrology of the ORB and OLRS operations, using a long series of climate data described in the previous chapter. The frequency of annual maximum water levels in the mainstem lakes and flow in the Okanagan River is assessed to estimate a range of ARIs, with recommendations for still-water lake level and river flow design values, used as input in the subsequent chapters.
- Chapter 4 – Lakeshore Floodplain:
  - This chapter describes the assessment of available wind and atmospheric pressure data in the ORB, the estimation of northerly and southerly design wind speed ARIs, and the generation of a spatially-varying wind field applicable to the lakes. The still-water design lake levels from the previous chapter are used as a base level, with storm surge (wind setup) and waves simulated to estimate wave runup on the lake shorelines. The resulting design levels are provided for the floodplain mapping. The potential for tsunami driven waves in Okanagan Lake is discussed.
- Chapter 5 – River Floodplain:
  - This chapter describes the development of a hydraulic model for the Okanagan River from Penticton to Osoyoos Lake, which is used to simulate the conveyance of flow through the river and potentially its floodplain. The model simulates the design flow

ARIs from the hydrology chapter to estimate depth of water in this area and the extent of design level flooding for the floodplain mapping. The hydraulic model is also used to simulate the hazard of flow through the floodplain for certain ARIs, through assessment of both flow depth and velocity.

- Chapter 6 – Floodplain Mapping & Applications:
  - This chapter describes the floodplain mapping process and provides guidance on the application of the floodplain mapping to reduce flood risk. This includes both structural and non-structural mitigation measures. This section also introduces a public website that has been developed as a part of this study to inform the public about flood hazard potential, and to provide comprehensive resources to reduce their flood risk. The website includes the floodplain mapping layers from this study.
- Chapter 7 – Primary Recommendations:
  - Chapter 3 through to Chapter 6 provide detailed recommendations at the end of each chapter for those study components. The reader is referred to each of those chapters for a complete list of recommendations as these are not re-summarized in this chapter. This chapter provides the main recommendations from this study with additional details to assist in any future work.

1.2 Objectives

The purpose of this project is to develop informational tools pertaining to ORB flooding to enable the various levels of government, local businesses, institutions, and residents to prepare for and hence reduce the risk of floods events.

The primary objectives of this study are to:

1) Develop floodplain maps for the Okanagan Lake and River system watershed, based on historic observations, and for a future time period subject to projected climatic changes; and

2) Improve the understanding of flood management options available to Okanagan water managers and operators, in the face of climate variability and change.

1.3 Study Area

The study area encompasses the Okanagan River basin down to the United States border (Figure 1-1), with the scope of the floodplain mapping including the Okanagan River mainstem lakes (Ellison/Duck, Wood-Kalamalka, Okanagan, Skaha, Vaseux, and Osoyoos) and Okanagan River from Penticton to Osoyoos Lake. The study includes the effect of backwatering by Similkameen River into Osoyoos Lake.

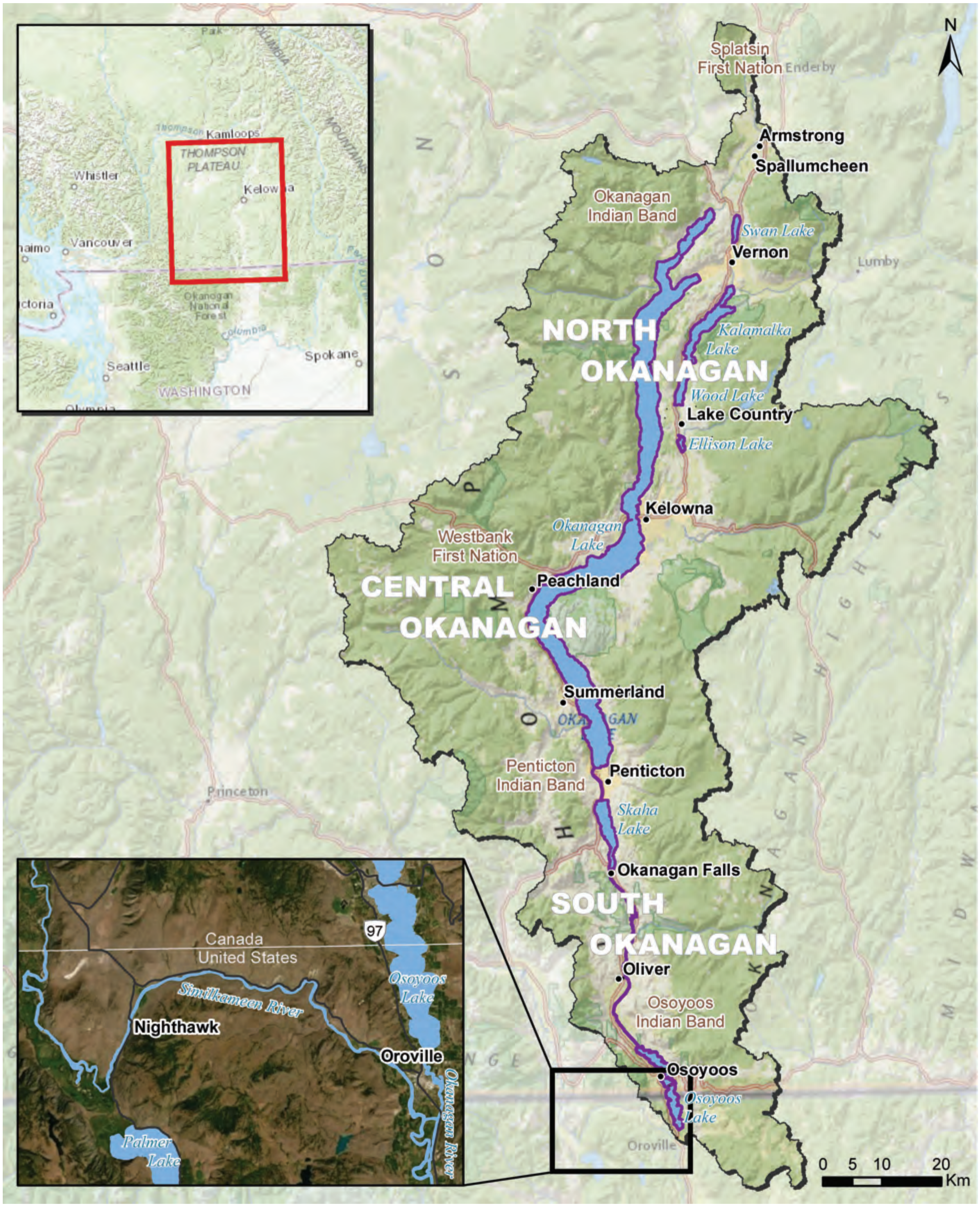

Figure 1-1 **Study area showing floodplain mapping extents (purple outline on main map), along with detail of the Similkameen River and Okanogan River confluence (bottom left).**

1.4 Project Limitations

Floodplain hazard mapping, assessment of flood risks, identification of mitigative options, and hydrologic and hydraulic modelling to support such work are core services for NHC. This study has been completed with ongoing review from OBWB and its TAC, FLNRORD, NHC's internal review team, and external experts noted in the Credits and Acknowledgements section.

The study and its deliverables are subject to the general limitations outlined below. Further detail on the assumptions, uncertainties, and limitations of each component of the study are provided within each component's chapter, and notes provided on the floodplain mapping index sheet must be reviewed prior to use:

- Refer to the DISCLAIMER following the signature page.
- In cooperation with FLNRORD, the operator of the OLRS, preliminary modifications to the OLRS Operating Plan and guidelines were made in this study to mitigate the expectation for higher and more frequent floods in the future. The results of this study and the floodplain mapping is contingent on such modifications, and without them, the design flood level for Okanagan Lake for example, would be 0.45 m higher. For the study's floodplain mapping to be applicable to the study area, it is assumed that these modifications to the OLRS Operating Plan and guidelines will be undertaken. These preliminary modifications are an initial step, however, and only consider flood control; further work is recommended to review how this can be balanced with First Nations, fishery, agricultural, and recreational interests. It is recommended that this be reviewed within the next five years, given the projected rate of change in floods due to a changing climate.
- The models developed in this study are based on current land-use conditions and historic data, and changes to land-use or new information or data may require the model be updated.
- There may be some errors in the data and software used in this study that have not been identified.
- Model simulations for historic, mid-century, and end-of-century conditions use synthetic climate that could have occurred historically and plausible climate that could occur in the future, given current assumptions on increases in greenhouse gas concentrations in our planet's atmosphere; what climatic conditions will exist in the future is not actually known.
- The models have been developed based on a limited set of historical extreme flood events. Consequently, the accuracy of the models to simulate some of the extreme flood events generated with the synthetic climate data, particularly for the events greater than the historical events that were calibrated to, is not known.
- The model simulates the real-world, but it has not yet been used to examine real-world challenges that could be encountered by an OLRS operator, such as dynamic adjustments in operations needed to manage flood risk in the system or prevent catastrophic damage to infrastructure downstream of Okanagan Lake due to high flows.

- Average recurrence interval values estimated for design are based on model simulations and extrapolation of frequency analyses, and therefore the resulting design values have an inherent uncertainty.
- The floodplain mapping is based on a bare-earth representation of topography (buildings have been removed), with further generalizing assumptions made for some of the mapped areas, including lakeshore areas that are exposed to wave effects. New development or re-development requires a site-specific flood hazard assessment.
- The occurrence of flood events larger than the flood-of-record for any areas in the study, require a reassessment of the floodplain mapping.
- The simulation of flow regulation is based on current and preliminary future operational guidelines. Changes in these current and assumed operations or flow controls could alter the presented results.
- Residual risk, greater than that shown in this report, exists; that is, a more extreme event (larger average recurrence interval) or sequence of events could result in higher flood levels and greater flood inundation than that mapped.

This document should be read and understood in its entirety before applying the maps, models, or other findings or results from this study. The reader is advised to seek the advice of a Qualified Professional to understand the study, its results, and the implications of any assumptions, uncertainties, and limitations.

1.5 Background and Past Relevant Studies

The Okanagan River mainstem area is British Columbia's largest interior population centre and a water-stressed environment; thus, a large body of water resources work has been performed in this region. A subset of previous studies most relevant to the current study, includes:

- Hydrologic and hydraulic models developed for the region for a range of purposes;
- Short term and seasonal flow forecasting models developed for the region and operated by RFC;
- Dam operation protocols developed for flood control;
- Extensive water demand and accounting models;
- An updated hydrologic model for 19 focus watersheds surrounding Okanagan Lake released at the time of publication of the current study (Associated Environmental, 2020).

Our work has built upon the knowledge from this prior work and incorporates new data and tools to assess historical and future flood risk on the Okanagan River mainstem.

The following subsections provide NHC's understanding of background information on the region.

1.5.1 Climate

The Okanagan watershed lies in a high plateau of BC's Southern Interior region, located in the rain shadow of the Coast and Cascade mountain ranges. The watershed receives lower precipitation than most regions in BC, and experiences large evaporation losses during its hot summers. Estimated mean annual precipitation rates range spatially from 300-400 mm in the southern valley (e.g. about 320 mm at Osoyoos) to 800-1,000 mm at the highest plateaus (and surpassing 1,000 mm at the high-elevation Mission Creek headwaters, Summit Environmental Consultants Inc., 2010), with a basin-wide average estimated around 600 mm (Alexander et al., 2013). The southern areas are driest, vegetated by sagebrush, perennial grasses, and cactus, while the somewhat wetter and cooler northern areas grow cedar and hemlock trees. The southern region between Oliver and the US border is classified as the Great Basin Biome.

With low average precipitation and high evaporation, the large and increasing Okanagan basin population has among the lowest water availability per capita in Canada. The annual hydrograph is dominated by the spring freshet, with April-June inflows representing roughly 90% of annual inflows to the Okanagan Lake and River system (Dobson, 2004). Inflows are low for all other seasons; hence all water uses depend on lake storage of spring snowmelt runoff.

The year-to-year variability of inflow volumes to Okanagan Lake, is of great importance to this project. Estimated annual inflows vary by more than an order of magnitude, from a minimum of 78 million m^3 in 1929 to 1.4 billion m^3 in 1997 (volumes which translate to 0.23 m to 4.12 m of lake storage, Symonds, 2018).

1.5.2 History of Flooding

Flood records within the ORB go back as far as the Osoyoos Lake area flood-of-record of 1894 (Septer, 2006). Flooding around Okanagan Lake and Kalamalka Lake and different individual creeks (including Mill, Mission, Joe Rich, Shorts, Vernon, and McDougal Creeks) has occurred in May and June in different years, and in July in the case of 1997. Some flooding events were associated with snowmelt, others due to rainfall, rain-on-snow, or a combination of rain and snowmelt. There were also instances of debris flows in the Okanagan Lake watershed in 1951 and 1997 (Septer, 2006).

A detailed analysis by NHC (2020a) of the available meteorological and hydrologic data for the largest historical floods prior to 2017 in Southern BC – in 1894, 1948 and 1972 – concludes that rapid snowmelt in May due to temperatures above average for the month, occurring after a colder than usual winter and spring, were factors common to all three of these flood events. Extremely high winter (October to May) precipitation did not appear to be a necessary condition, although above normal winter precipitation was common to both the 1948 and 1972 floods. Although information about precipitation for the 1894 flood was very limited and uncertain, the data available for the 1948 and 1972 floods was clear on the role of rapid snowmelt in generating the historical floods in these years. Rainfall during the peak melt period in late May or early June was an additional contributing factor on the Columbia in both the 1948 and 1972 floods, but temperature anomalies were still the main forcing influence.

Photo 1-1 Historic photograph from Kelowna Museums for the reader's interest (not referenced in text), description in the museum's records reads: "View of the corner of Bernard Avenue and Abbott Street during the 1903 flood. Woman riding side saddle past the Kelowna Shippers Union building is Mrs. Pooley. This was the flood high point." Kelowna Public Archives: KPA#80 – <u>licensing required for image use</u>.

A study by Associated Engineering (Associated Engineering, 2016), which reviewed historical floods of the Okanagan, found that potential additional causes of flooding are debris blockages followed by rapid release of flows, ice jams, dike breach, dam break, sediment accumulation, surge and wave effects during high lake levels, and climate change; factors which can also be affected by land-use changes. There are 129 dams within or upstream of RDCO, including several high-consequence (and one extreme-consequence) dams. Most of these undergo regular DSR studies.

The most recent floods of 2017 and 2018 involved early snowmelt peaks, which are atypical and suggest the need for adaptation. The 2017 event led to the highest level ever recorded at Okanagan Lake, 343.25 m CGVD28 (343.49 m CGVD2013 at Kelowna). This is higher than the full pool elevation of 342.48 m CGVD28 (342.72 m CGVD2013 at Kelowna) and dangerously close to the lake's flood construction level of 343.66 m CGVD28 (343.90 m CGVD2013 at Kelowna) (AE, 2017b). Kalamalka Lake rose to a peak of 392.45 m CGVD28 (392.70 m CGVD2013 at gauge), which is 0.25 m above the estimated 200-year ARI elevation (392.2 m CGVD28), and within 0.75 m of the FCL (393.2 m CGVD28) (AE, 2017b).

The 2018 event also resulted in high lake levels at Okanagan Lake, 342.69 m CGVD28 (342.93 m CGVD2013 at Kelowna), which is the fifth highest level on record (Symonds, 2018). The extraordinary event of 2017, which led to the highest level ever recorded at Okanagan Lake, was due to high lake storage levels prior to (unanticipated) large late-season snow accumulation, along with early melt and rainfall. Wet soils and high-water tables due to plentiful rainfall in October of 2016 also contributed to high runoff production in 2017. The challenges posed to water managers by the 2017 event are reviewed in section 1.5.4.

1.5.3 Challenges in Operation Decisions

Operations of the Okanagan and Kalamalka Lake dams are guided by five competing objectives:

- Flood control,
- Irrigation water supply,
- Aquatic ecosystem needs,
- First Nations interests, and
- Recreation.

Every year starting on 1 February, the RFC issues forecasts of lake inflow to the Okanagan and Kalamalka lakes, which is used by regional water managers. Forecasts are issued for the period from the forecast date through the end of July. These forecasts are later updated on 1 March, 1 April, and 1 May. The forecasts use regression equations, fit via principal components regression, based on four predictors: upper elevation snowpack; rainfall in the preceding fall season (which influences soil saturation and therefore runoff response); low-elevation precipitation during winter (which influences runoff in early spring); and current stream flows (generally baseflows). The models do not use weather forecasts and assume that future conditions will be average for the time of year.

To make decisions for the rate of flow release from each lake, an OLRS water manager considers the inflow forecasts, the ecological flow requirements in the downstream channel, and the reservoir storage goals of flood control and water supply reserves. Each of these factors varies over time, hence water managers periodically adjust the lake outflow rates. The decision process is assisted by an important computational tool, FWMT (Alexander et al., 2013; Hyatt et al., 2015), which includes five coupled models, four of which are biophysical models representing relationships between climate, fish and water, and the fifth being a water management rules model. The FWMT runs these five models (to which it inputs real-time observed data, including lake elevation, river flows, snowpack and precipitation) to predict consequences of alternative water-release decisions for fish and for lake storage, the latter on which depend the other water uses.

For Okanagan Lake, water managers use forecasted inflows and the Operating Plan (which calculates outflow decisions based on the forecasts), FWMT, and their own observations and judgement to make decisions on lake outflows. The FWMT informs water managers of the time-varying needs of aquatic ecosystems downstream of the lakes and near the lake shores. The FWMT disaggregates the RFC forecast inflow volume into daily inflow hydrographs, by sampling daily inflows from a previous year that the model's Real-Time Statistical Matching (RTSM) algorithm has identified as a close match to the current year in terms of total volume and temporal distribution of flows. The daily forecast inflows are then aggregated to weekly inflows for use by the water managers. Given these forecast weekly inflows, managers can then study the effects of outflow rate decisions on lake storage.

Potential flow release schedules are reviewed by FLNRORD, DFO, ONA (i.e. the FWMT team) and discussed amongst these groups. The responsibility and final decision remain with the water manager (of FLNRORD), who gives direction to set the gates to achieve the desired outflow. Between this time and the next RFC forecast, the estimated daily and weekly inflows are replaced with the actual observed inflows, which may lead to the water manager updating the flow release schedule even prior to the next RFC forecast.

In this process there are several major challenges. Natural variability of inflows to the lakes is large (ranging more than an order of magnitude) and it is difficult to predict for any given year since the inflow forecasts are quite uncertain in both volume and timing. The Okanagan Lake has limited total active storage volume for reliably meeting its competing objectives. The limited volume coupled with limited maximum discharge capacity and limited river channel capacity downstream (sometimes further limited by large streamflows produced downstream of Penticton) compared to peak inflows to Okanagan Lake makes water management vulnerable to unanticipated extreme weather events – such as prolonged intense rainfall, copious snowfall late in the season, and the occurrence of strong winds. The year of 2017 exemplified these difficulties (see section 1.5.4).

The statistics of year-to-year variability in inflow volumes to the lakes convey the challenge faced by managers. In approximately one of every four years, it is necessary to release from Okanagan Lake a volume larger than half of that year's incoming freshet to avoid flooding (Hyatt et al., 2015). On the opposite side of the problem we have that in approximately one of every three years the storing of the entire freshet volume is insufficient to meet dry season water requirements, i.e., the combined needs of aquatic ecosystems and human systems, in a basin with one of the lowest water availability per-capita in Canada (Hyatt et al., 2015). Given such contrasting sets of decisions to be made in wet versus dry years, and the uncertainty inherent to inflow forecasts, water managers face stark challenges.

In wet years, releases from Okanagan Lake must be started sufficiently early, because the outflow rate should be limited to a maximum of 60 m^3/s. While the dam outlet can release at 77.9 m^3/s or even higher when lake levels are high, this poses risks to Okanagan River dykes south of Penticton. Alexander et al. (2013) describes the situation as follows: *"…the average net May inflow (…) is close to 88 m^3/sec^{-1}* (sic), *which is about 28 m^3/sec^{-1}* (sic) m*ore than Okanagan Lake dam can release. If the extra 28 m^3/sec^{-1}*

(sic) c*ontinued for a full month, it would raise Okanagan Lake's elevation by 21 cm. Furthermore, the average inflow ignores the large interannual variation – short-term inflow rates greater than 250* m^3/sec^{-1} (sic) a*re not unheard of."* Therefore, lake levels need to be lowered during the late fall and winter, in anticipation of a possible large freshet.

High discharge rates during sensitive phases of the life cycle of salmon also need to be avoided, given the important cultural, ecologic, and economic value of basin fisheries, and the investments that have been made to restore the Okanagan sockeye population in particular (whose low numbers, now significantly recovered, had led the Okanagan to be declared one of the most endangered rivers in Canada in the 1990s). The Okanagan Lake and River system contains a large fraction of the breeding habitat for the sockeye population of the Columbia River.

Management of Osoyoos Lake, straddling the US/Canada border, is also challenging. The level of Osoyoos Lake is controlled by Zosel Dam, whose operation is supervised by the International Osoyoos Lake Board of Control established by the IJC. The Order of Approval for Zosel Dam, which specifies operating rules for the dam, was updated by the IJC in 2013 with input from the 2011 Osoyoos Lake Water Science Forum. According to the operating rules, Osoyoos Lake is required to stay within specified maximum and minimum bounds to the extent possible, and the operator must consider multiple goals including agriculture, water supply, ecology, and recreation. Maintaining Osoyoos Lake between the stipulated bounds represents a challenge, and the summer upper maximum of 912 m NGVD 1929 (278.10 m CGVD2013) was exceeded in both 2017 and 2018.

1.5.4 The Events of 2017 and 2018

In the spring of 2017, the southern interior region of BC experienced widespread flooding due to prolonged rainfall. In the Okanagan River basin, the 1 February and 1 March 2017 forecasts indicated below-average to average inflows to the lakes. This was determined by the below-average winter snow accumulation at the high-elevations, which normally produce the most snowmelt runoff and on which the forecasts relied. However, snow accumulation at lower elevations (not considered for the forecasts) was in fact above normal. Plentiful precipitation during April brought rainfall to the lowlands and raised the highlands snowpack by an estimated 50% in the Okanagan Lake watershed. In May, rainfall continued, snowmelt was plentiful, and water tables were high, producing the highest lake inflows on record.

Up until April, decisions by the water manager were in accordance with the Operating Plan, which calculates outflows based on the inflows forecast. In April, observing much higher inflows than had been forecast, the water manager appropriately deviated from the Operating Plan, increasing the outflow. By early May, lake outflow had been increased to nearly the maximum rate that the downstream channel can sustain without significant damage and flooding. May inflows to the lake were the highest on record, leading to (AE, 2017b):

- A record-breaking lake level of 343.25 m CGVD28 (343.49 m CGVD2013 at Kelowna):

- This level is higher than the full pool elevation of 342.48 m CGVD28 (342.72 m CGVD2013 at Kelowna), and,
- Is only 0.41 m lower than the 1991 floodplain mapping flood construction level of 343.66 m CGVD28 (343.90 m CGVD2013 at Kelowna), which was intended to provide 0.61 m of freeboard.

The 200-year ARI lake elevation had been estimated at 343.05 m CGVD28 (343.29 m CGVD2013 at Kelowna, BC Water Resources Service, 1974).

Fortunately, the subsequent month of June had below-average rainfall, and the flood construction level was not reached. Photo 1-2 and Photo 1-3 on the following pages show Okanagan Lake levels around the time of the 2017 peak, in the area immediately west of the Okanagan Lake Dam and also further east at Penticton's beachfront; the photo captions provide further detail on relative water levels and dates.

Photo 1-2 Areas immediately west of the Okanagan Lake Dam around the time of the 2017 peak (June 8), clockwise from top-left: looking north at sandbagging along the perimeter of the lake (June 2); same area with increased sandbagging 3 days later (June 5); looking south along the lake shoreline towards Okanagan Dam (June 2); and the Okanagan Lake Dam a month earlier (May 7). The June 2 and 5 average water levels were respectively 83.3 and 0.864 m higher than on May 7; the 2017 instantaneous peak Okanagan Lake water level on June 8 was 0.027 m higher than the June 5 mean water level. Photo credits: Mike Noseworthy, FLNRORD.

Photo 1-3 Okanagan Lake Penticton beachfront photos around the time of the 2017 peak (June 8), clockwise from top-left: looking southwest from Rotary Park (June 6); flood protection in the Penticton Rose Garden, immediately east of the Okanagan Lake Dam (May 29); and looking northeast from Rotary Park (June 6). The 2017 instantaneous peak Okanagan Lake water level on June 8 was 0.026 m higher than the June 5 mean water level. Photo credits: Mike Noseworthy, FLNRORD.

At Kalamalka Lake the water manager also increased outflows to the flow capacity of Vernon Creek by early May. Inflows in May were the highest on record and the lake level reached 392.45 m CGVD28 (392.70 m CGVD2013 at the WSC Kalamalka Lake gauge), which is (AE, 2017b):

- 0.75 m below the flood construction level of 393.2 m CGVD28 (393.45 m CGVD2013 at the WSC Kalamalka Lake gauge), and
- 0.25 m above the estimated 200-year ARI elevation of 392.2 m CGVD28 (393.45 m CGVD2013 at the WSC Kalamalka Lake gauge).

In 2018 (a year that better fit the typical wet-year profile) the inflow forecast did predict large inflows (in contrast with 2017) based on the usual predictor, the high-elevation snowpack. In anticipation of these large inflows, Okanagan Lake was drawn down sufficiently early, as per the guidelines. Nevertheless, to achieve sufficiently low levels, it was necessary to override the fisheries guidelines in April 2018. In mid-May, tributary inflows into Okanagan River were unprecedented, and it was necessary to slow down the outflows from Okanagan Lake.

At Zosel Dam, the operating rules established by the IJC require that Osoyoos Lake stay within maximum and minimum bounds to the extent possible. The summer maximum bound of 912 ft NGVD 1929 (278.10 m CGVD2013) was exceeded in both 2017 and 2018, when the lake level reached 914.87 ft (278.97 m CGVD2013) and 916.38 ft (279.44 m CGVD2013), respectively. The high lake level in 2018 was due to a combination of high inflow to Osoyoos Lake from the Okanagan River and extremely high flow rates on the Similkameen River and the resulting backwater effect. We note that the maximum lake level of 2018 was surpassed in both 1972 (maximum lake level of 917.11 ft NGVD 1929, or 279.66 CGVD2013) and 1894 (estimate maximum lake level of 918.8 ft NGVD 1929, or 280.17 CGVD2013).

1.5.5 Review of Previous Studies and Models

A large body of work has been produced for the Okanagan River mainstem region regarding hydrology, hydraulics, water supply and demand, and climate. Since approximately 2004, a number of in-depth studies have advanced the state of knowledge on the hydrology and water resources of the Okanagan River basin. Some salient studies and reports, which have informed this study, are included in the following annotated bibliography. A few key figures published in the reviewed literature are also reproduced in this section.

Okanagan Water Supply and Demand Project (OWSDP)

The OWSDP was a major project undertaken over the course of several years (approximately, 2005-2010), contributing to great insight into ORB hydrology, water resources and demand, and their dependence on climatic and human factors. The OWSDP produced a suite of models (reviewed below) and detailed reports[1] covering information on the ORB water balance components, surface and groundwater resources, water use, and instream flow needs, under present and future scenarios of

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[1] https://www.obwb.ca/wsd/about/project-reports, accessed 31 March 2020.

climate and demand. These were the first models to be developed and applied in Canada for such a large watershed, and the OWSDP was the recipient of the 2012 “Award of Excellence” by the BC Water and Waste Association.

Phase 1 scoped user needs (Summit Environmental Consultants Ltd., 2005), Phase 2 conducted the water resources research and model development (Summit Environmental Consultants Inc., 2010), and Phase 3 used those models to explore the implications for water supply and demand of future scenarios of climate, population and land-use (Polar Geoscience, Ltd., 2012). Two figures that summarize the estimated water balance for the watershed and for Okanagan Lake on the basis of the OWSDP project, are reproduced here in Figure 1-2 and Figure 1-3.

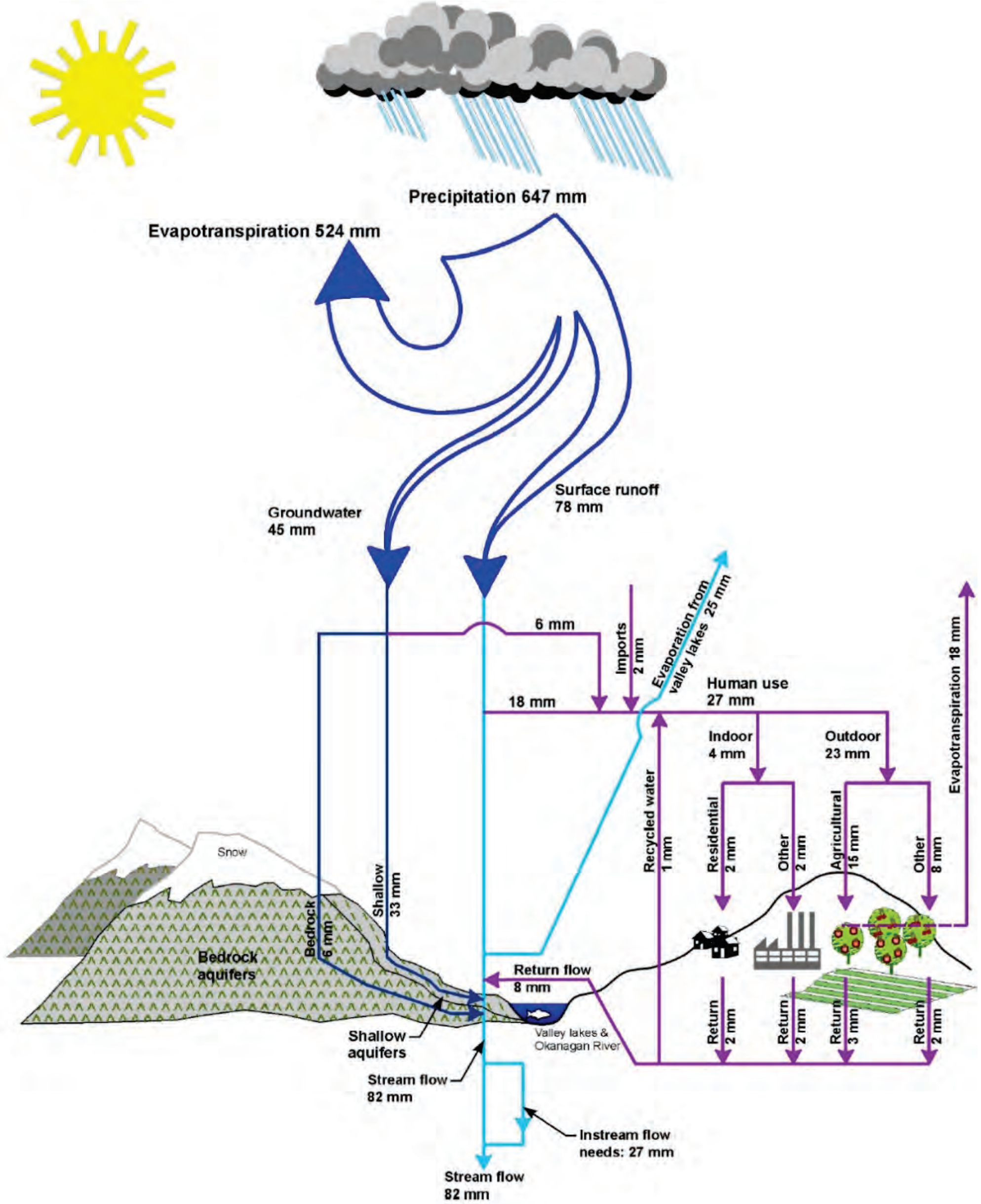

Figure 1-2 ORB water balance estimated in the Okanagan Water Supply and Demand project (OWSDP), based on the 1996-2006 period. Units are depth (millimetres, mm) over the area of the land. This figure is reproduced from the OWSDP Phase 2 report (Figure 6.1 in Summit Environmental Consultants Inc., 2010). As stated elsewhere in that same report, the figure indicates the average estimated water balance, and does not attempt to portray the variability which characterizes both supply and demand.

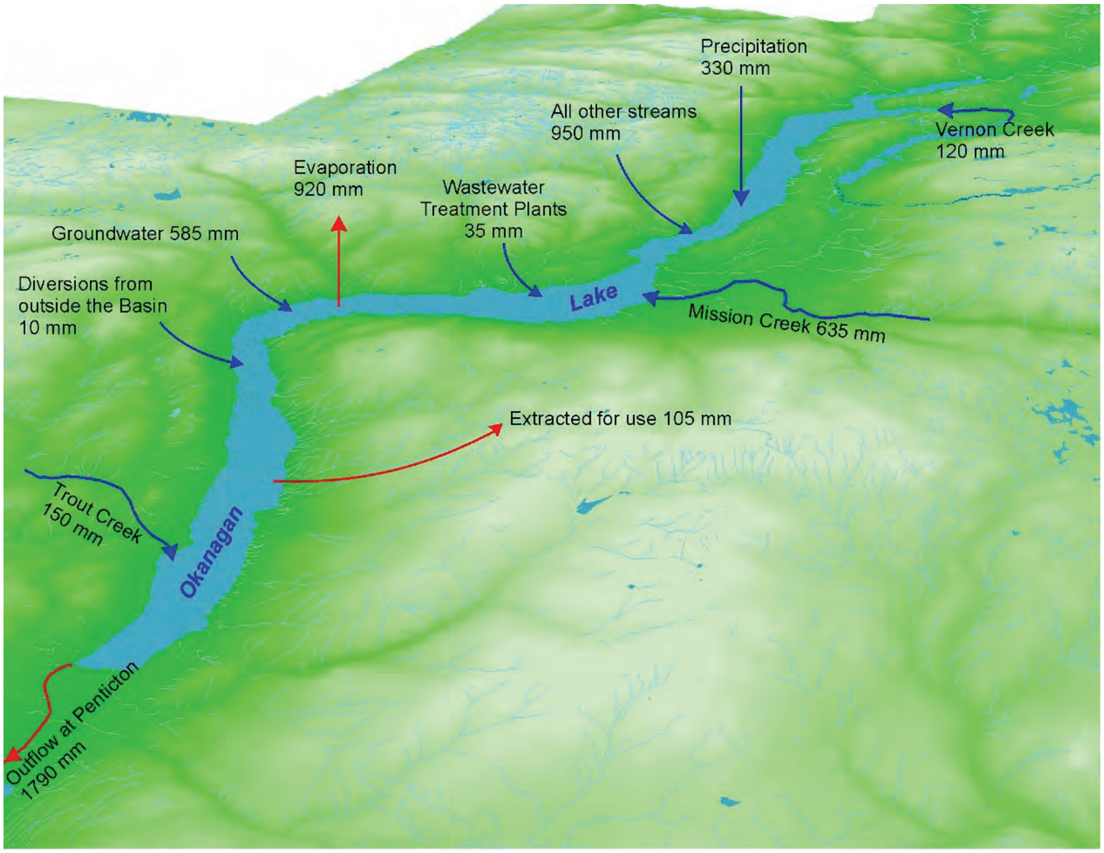

Figure 1-3 Okanagan Lake water balance estimated in the Okanagan Water Supply and Demand project (OWSDP), based on the 1996-2006 period. Units are depth (millimetres, mm) over the area of the land. This figure is reproduced from the OWSD Phase 2 report (Figure 6.2 in Summit Environmental Consultants Inc., 2010). As stated elsewhere in that same report, the figure indicates the average estimated water balance, and does not attempt to portray the variability which characterizes both supply and demand.

Okanagan Basin Hydrology Model (OBHM)

The OBHM is a grid-based hydrologic model developed using the MIKE SHE/MIKE 11 platform (DHI Water & Environment, 2010) used for estimating current and future water supply in the ORB. The OBHM was calibrated against estimated naturalized conditions for eight natural streams for 1996-2006 (which were developed in the Hydrology State of the Basin Report, given in Appendix G[1] of the OWSDP Phase 2 report), and snow water equivalent data at 21 locations for the same period 1996-2006. Model simulations of various water cycle components were compared against previous estimates (in

Appendices[1] C, D, E, F1 and F2 of the OWSDP Phase 2 report; Summit Environmental Consultants Inc., 2010).

OBHM's simulated naturalized streamflows are input to the OBWAM, which assesses water supply and demand in the ORB (as described below). Grid resolution is 500x500m, chosen to match the gridded climate datasets developed for the ORB (described below) used to force the model. Aquifers are not partitioned by this grid and are represented conceptually as linear reservoirs (described in Appendices[2] D and E of the OWSDP Phase 2 report). PET was represented by a modified Penman-Monteith equation. Lake evaporation is estimated with the Penman-Monteith equation (as is also the case in the OWDM, described below).

Okanagan Water Demand Model (OWDM)

The OWDM[3] simulates water demands for all outdoor and indoor purposes, such as agricultural, industrial, and domestic water demands under current and future scenarios of climate and population (BC Ministry of Agriculture and Agriculture and Agri-Food Canada, 2010). Climate is the main driver of variability in water demand (as well as supply). The model accounts for thousands of land parcels and hundreds of water use areas, linking the water used by each water use area to its water source and calculating the weekly need for water from that source to satisfy the demand from all water use areas. The core of the OWDM is the Agriculture (Irrigation) Water Demand Model (Van der Gulik et al., 2010), which is based on a GIS database containing information on local crop type, irrigation system, soil texture, and climatic data. Non-agricultural green spaces are also included. Evaporation from lakes is estimated with the Penman-Monteith equation (as in the OBHM, above).

Okanagan Basin Water Accounting Model (OBWAM)

The OBWAM combines the OBHM's simulated naturalized streamflows with OWDM's water demand estimates, to account for the effects of water extractions (from surface and groundwater resources) and reservoir operations. The OBWAM uses this information to estimate streamflows in tributaries and the Okanagan River, and storage levels on the main lakes. Like OBHM, it is also based on the MIKE SHE platform. The OBWAM is described in the report by DHI Water & Environment (2010) and Appendix B[1] of the OWSDP Phase 2 report. The OBWAM simulations were verified against observed streamflow and lake levels, and several of its key components were verified against the results of separate studies for the calibration period 1996-2006 (Appendices[4] C, D, E, and I of the OWSDP Phase 2 report). The human influences accounted for in OBWAM include:

- Water extractions from surface water and groundwater;
- Flow releases from the upper reservoirs;

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[1] https://www.obwb.ca/wsd/about/project-reports, accessed 31 March 2020.

[2] https://www.obwb.ca/wsd/about/project-reports, accessed 31 March 2020.

[3] https://www.obwb.ca/wsd/models/okanagan-water-demand-model, accessed 31 March 2020.

[4] https://www.obwb.ca/wsd/about/project-reports, accessed 31 March 2020.

- Surface return flows, including municipal wastewater discharge to Okanagan Lake and Okanagan River;
- Groundwater return flows, including return of irrigation water and septic system discharge; and,
- Water imports from outside the ORB.

Results of the calibration of the OBWAM to the mainstem lake levels and Okanagan River discharges for 1996-2006 are shown in two figures in the OWSDP Phase 2 report (Summit Environmental Consultants Inc., 2010), which are reproduced here in Figure 1-4. Calibration is reported as being *"challenging"* in the OWSDP Phase 2 report. This is explained in section 16 of that report as follows:

> *"The data quality of the lake levels and river discharges is good, and the operational rules are well documented in dam operating plans, but implementation of the rules is at the discretion of the dam operator. As a result, there are some observed lake levels which could not be reproduced by the model because the observed levels contradict the written rules by which the lakes are supposed to be operated. Therefore, the calibration of the operational rules involved several iterations to find the right combination of rule priorities, frequency of gate adjustment, and gate level increment schemes. (…) Figure 16.2 shows a plot of the simulated vs. observed water levels at Okanagan Lake, and Figure 16.3 shows a plot of the simulated vs. observed discharges from Okanagan Lake at Penticton. Calibration plots and statistics for lake levels and discharge from the other mainstem lakes (Kalamalka, Skaha, Vaseux, and Osoyoos) are included in Appendix J.*
>
> *For Okanagan Lake, the lake level shows a very good fit during normal and wet years, but the model tends to under-predict lake levels during dry years. Many attempts were made to correct this behaviour in the model and some success was achieved by adjusting the operational rules and settings, as well as incorporating inflow volume forecasting. However, a closer examination of the observed response vs. the documented operational rules indicated that, during dry years, the operation of the dam diverged from the operational rules. Since the logic used to operate the dams during these times was not specifically documented, it was not possible to incorporate it into the model."*

It is valuable to the present study to recognize the difficulties inherent to simulating operation decisions, such as described above. Since the decision-support system FWMT has been in use since 2003 (Hyatt et al., 2015), the retrospective simulation of reservoir releases from 2003 to present faces a different degree of complexity or set of challenges for the current study.

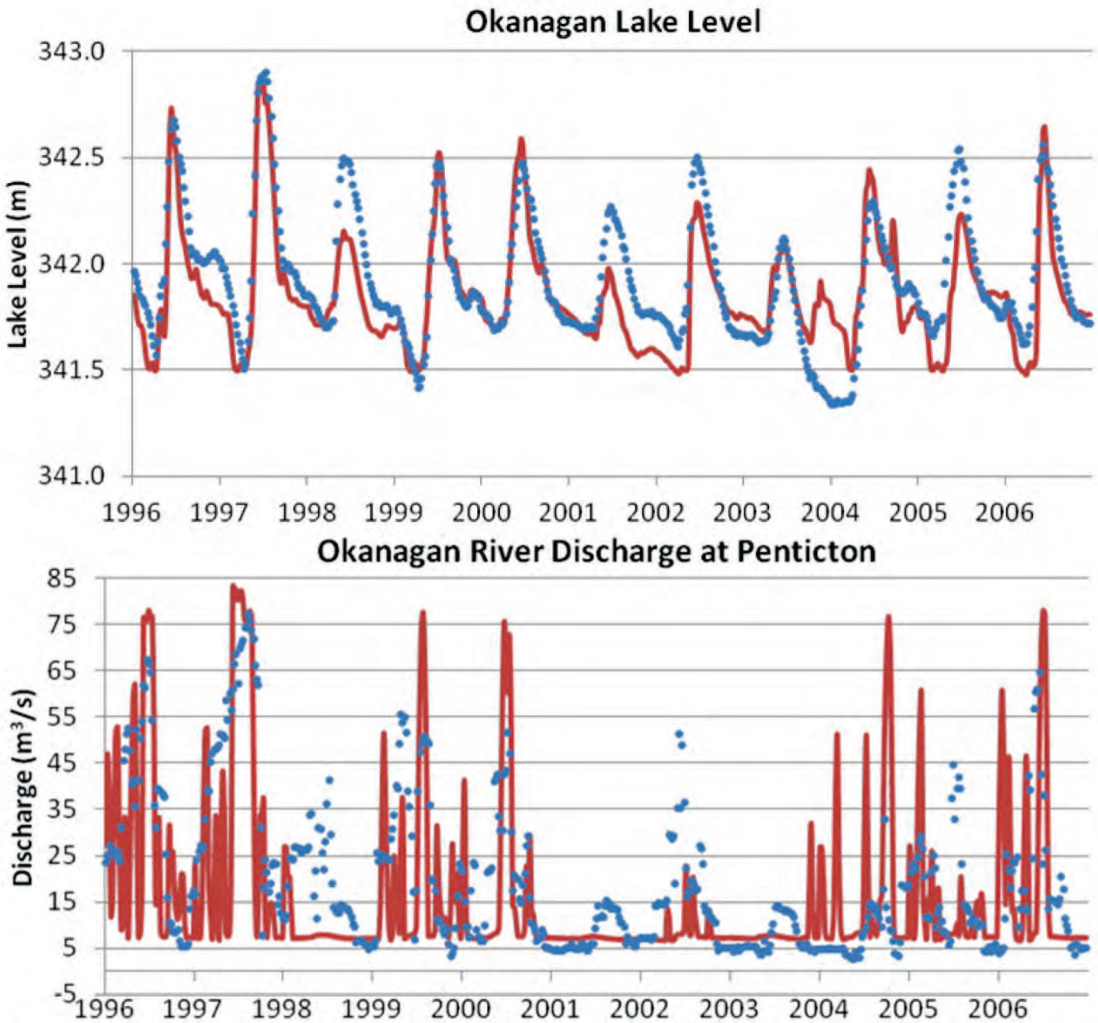

Figure 1-4 OBWAM-simulated (red) and observed (blue) Okanagan Lake levels (top panel) and Okanagan River discharge at Penticton (bottom panel). This figure is reproduced from Figure 16.2 (top panel) and Figure 16.3 (bottom panel) published in OWSDP Phase 2 report[1] (Summit Environmental Consultants Inc., 2010).

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[1] https://www.obwb.ca/wsd/about/project-reports, accessed 31 March 2020.

Okanagan Hydrologic Connectivity Model

The OHCM is based on the Water Evaluation and Planning (WEAP) platform[1] and uses output from the above-reviewed OBHM and OWDM (Summit Environmental Consultants Ltd., 2013a, 2013b). OHCM's intent is to provide a relatively rapid simulation and scenario evaluation. Simulations with OBHM are more time consuming. The OHCM was run under a number of scenarios to investigate the impact of different types of changes on water users in different subbasins. Changes in the storage of upper lakes, increased water demands, and increased instream flow requirements were studied. Impacts on users were studied dependent on user location and license seniority in the "first in time, first in right" (FITFIR) licensing system under the BC Water Act.

Fish and Water Management Tool (FWMT)

The crucial role played by the FWMT tool – fully implemented since 2003 – in assisting water release decisions that must balance multiple and conflicting objectives is made clear in Alexander et al. (2013) and Hyatt et al. (2015), as is the tool's success in aiding the recovery of fish species of concern. The FWMT tool is a software program that automates complex calculations (including time-variable biophysical targets for fish populations, estimates of fish life cycle timing such as egg-to-fry emergence, real-time data on inflows to Okanagan Lake, target and limits for discharge rates and lake levels) to provide a risk assessment framework. This includes anticipated socio-economic outcomes of management decisions for guiding water managers, and increasing cooperation between managers from government agencies, industry, and local communities.

The report by Alexander et al. (2013), while intended as guidelines for new water managers, represents an important source of information and insight for this study, especially pertaining to the challenges faced by Okanagan Lake management. The report describes:

- The key issues and science of ORB water management;
- The target minimum and maximum stream flows and their science (or other) foundation;
- The response of lake levels to different rates of net inflow;
- Guidelines for flow releases and how they allow balancing conflicting objectives;
- A retrospective simulation for evaluation of long-term model performance; and
- A users' guide to the FWMT software tool.

Hyatt et al. (2015), using a retrospective analysis, showed that implementation of the FWMT tool has significantly improved compliance of water management decisions with OBIA guidelines to protect salmon during critical egg-to-fry emergence stages. Figure 1-5 and Figure 1-6 are reproduced from Alexander et al. (2013) given their usefulness as reference material for the current study.

[1] https://www.weap21.org/, accessed 31 March 2020

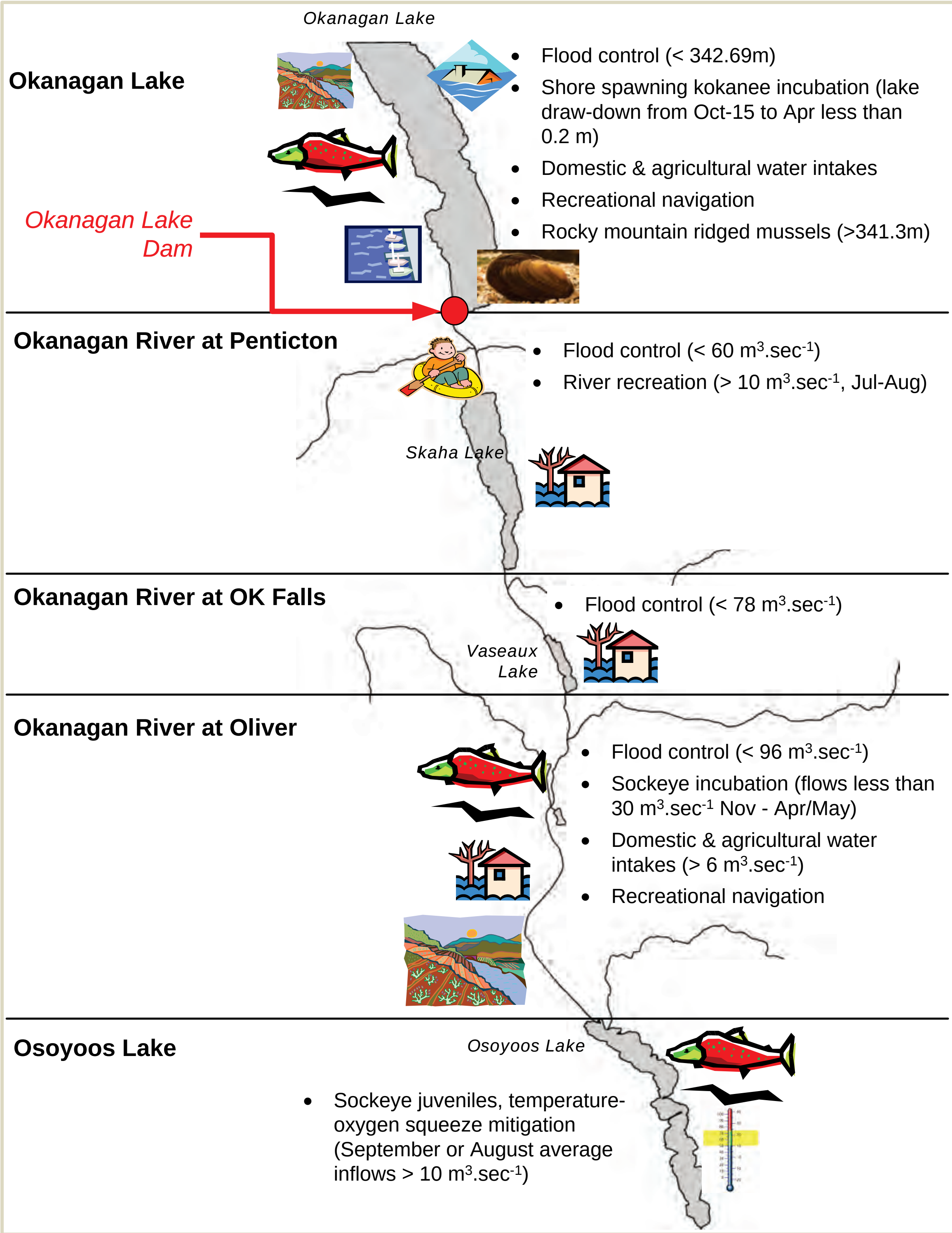


Figure 1-5 The five sections of Okanagan basin that are included in FWMT. The bullet points summarize the key fish/water management objectives that must be considered within each section. This figure and caption are reproduced from Alexander et al. (2013).

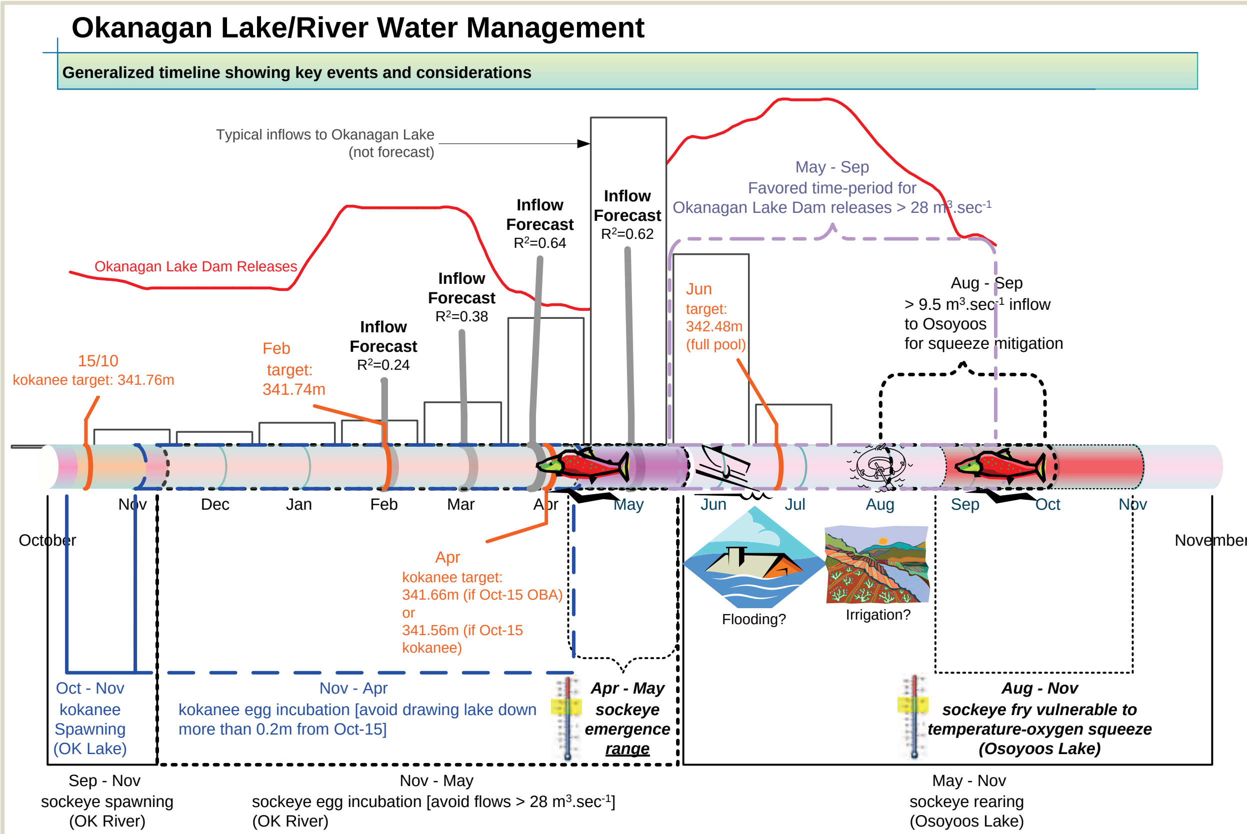


Figure 1-6 **Timeline for the annual management cycle of Okanagan basin, illustrating flood management, fisheries, irrigation and recreation considerations. The timing of various life-history intervals for kokanee and sockeye are not fixed—they vary year to year. A *stylized* Okanagan Lake dam release pattern is shown in red. The monthly net inflows (vertical bars) refer to actual average net inflows on a given month (not the inflow forecast). This pattern is highly variable year to year. The inflow forecasts for February, March, April, and May refer to the dates of those provided by the RFC. Figure 1-5 provides the geographic context. This figure and caption are reproduced from (Alexander et al., 2013).**

Lake Evaporation Studies

Evaporation losses from lake surfaces represent a large component of the Okanagan watershed water balance, and it is important to ensure that the simulation of time-varying evaporation rates in the Raven ORB model developed in the current study agrees with the best independent estimates. Therefore, review of the literature for independent estimates of lake evaporation was especially important and is summarized below. In conclusion from the review below, the most valuable information is the observations-based daily time series obtained by Spence and Hedstrom (Spence and Hedstrom, 2015) during a period of nearly three years when meteorological conditions were approximately average, and which provide monthly mean estimates of lake evaporation.

One of the goals of the 1974 Federal-Provincial Okanagan Agreement was to collect data and estimate water budgets for water resource planning (Stockner and Northcote, 1974). To that end, Ferguson et al. (1974) (cited by Schertzer and Taylor, 2009), estimated the mean annual evaporation from Okanagan Lake at 880 mm/year, based on corrected pan 1958-1974 evaporation data from the Summerland CDA climate station. However, heat capacity differences between lakes and pans, particularly the fact that pans are frozen over long periods while the Okanagan lakes do not freeze (except over localized bays), render these estimates inaccurate.

Trivett (1984) conducted a landmark study of evaporation from the Okanagan watershed lakes, using eddy covariance to relate over-lake measurements to offshore meteorological instruments over a 2-week period in September 1980, and calibrate the mass transfer equation $E = M \cdot u \cdot (e_s - e_a)$, where *E* is evaporation, *M* is the mass transfer coefficient (calibrated by Trivett), *u* is wind speed 4 meters above the surface, e_s is vapour pressure at the lake surface (mb), and e_a is the vapour pressure at 4 m above the lake surface (mb). Using the calibrated equation, Trivett calculated annual evaporation rates for the 1 year period 5 May 1980 – 4 May 1981 based on climatological data from the Kelowna A and Penticton A airport stations modified to represent conditions over each lake, and using data from the Summerland CDA evaporation pan. Estimates based on Trivett's (1984) method are listed near the end of Table 1-1.

Trivett (1984) showed that meteorological station observations are not representative of the meteorological conditions over the lake surfaces and recommended data collection studies. However, only 30 years later was another observations-based study published (Spence and Hedstrom, 2015), reviewed below. In the absence of key field data, subsequent studies – including the Environment Canada study by Schertzer and Taylor (2009) – required numerous uncertain assumptions concerning meteorology, energy fluxes, and limnology.

The Environment Canada study (Schertzer and Taylor, 2009) consisted of a review of 19 different methods for estimating evaporation from the lakes of the Okanagan watershed. The study showed a wide range of estimates across methods, summarized in Table 1-1, largely due to the lack of observational data to provide a sound basis for any method. Table 1-1 shows that for Okanagan Lake, estimates range from 271 to 1,227 mm/year for the period of study (1996-2006). Reliable evaporation estimates require accurate estimates of different variables, which are not generally available (Figure 1-7). Schertzer and Taylor (2009) issued renewed appeals for data collection studies.

Table 1-1 Summary of the mean annual evaporation rates (mm/year) and total evaporation (x 10^6 m^3/year) from the 6 mainstem lakes for the period 1996-2006 based on the 19 evaporation models. This table is reproduced from Okanagan Water Supply and Demand Project – Phase 2 – report, Appendix F (Table F1.4), which summarizes the results of the Environment Canada study (Schertzer and Taylor, 2009).

Group and Model	Model Abbr.	Kalamalka		Wood		Okanagan		Skaha		Vaseux		Osoyoos	
		Evap[1]	Vol[1]	Evap	Vol	Evap	Vol	Evap	Vol	Evap	Vol	Evap	Vol
Energy Budget													
Bowen Ratio	**EEB**	657.4	**17.03**	616.8	**5.74**	759.5	**264.30**	746.7	**15.01**	923.0	**2.54**	861.8	**12.93**
Combination													
Priestly-Taylor	**EPT**	632.2	**16.37**	612.7	**5.70**	668.4	**232.61**	729.5	**14.66**	818.9	**2.25**	782.7	**11.74**
deBruin-Keijman	**EDK**	647.4	**16.77**	627.5	**5.84**	689.5	**239.96**	751.6	**15.11**	834.4	**2.30**	801.9	**12.03**
Penman-Monteith	**EPM**	338.4	**8.76**	352.1	**3.28**	531.6	**185.01**	472.1	**9.49**	399.9	**1.10**	399.9	**6.00**
Penman	**EPN**	692.6	**17.94**	677.1	**6.30**	884.6	**307.83**	934.2	**18.78**	942.9	**2.59**	914.1	**13.71**
Penman Kimberly	**EPK**	688.6	**17.83**	657.8	**6.12**	728.0	**253.33**	765.9	**15.40**	793.1	**2.18**	764.3	**11.46**
Brutsaert-Striker	**EBS**	899.4	**23.29**	877.2	**8.16**	745.5	**259.43**	1023.6	**20.57**	1177.7	**3.24**	1150.6	**17.26**
deBruin	**EDB**	691.6	**17.91**	691.6	**6.43**	1226.7	**426.91**	1230.9	**24.74**	1046.1	**2.88**	1046.1	**15.69**
Solar Radiation – Temperature													
Jensen-Haise	**EJH**	782.4	**20.26**	782.6	**7.28**	880.2	**306.30**	883.7	**17.76**	971.8	**2.67**	971.8	**14.58**
Makkink	**EMK**	661.5	**17.13**	661.5	**6.15**	710.5	**247.24**	713.0	**14.33**	754.9	**2.08**	754.9	**11.32**
Stephens-Stewart	**ESS**	506.1	**13.11**	506.2	**4.71**	565.3	**196.73**	567.7	**11.41**	620.6	**1.71**	620.6	**9.31**
Turc	**ETU**	185.0	**4.79**	186.3	**1.73**	271.0	**94.31**	271.2	**5.45**	280.9	**0.77**	280.9	**4.21**
Temperature – Day length										*			
Hamon	**EHM**	612.4	**15.86**	612.4	**5.70**	660.1	**229.73**	657.6	**13.22**	706.3	**1.94**	706.3	**10.59**
Blaney-Criddle	**EBC**	791.4	**20.50**	791.5	**7.36**	883.0	**307.29**	881.5	**17.72**	956.6	**2.63**	956.6	**14.35**
Temperature													
Papadakis	**EPA**	826.4	**21.40**	826.1	**7.68**	910.2	**316.74**	910.4	**18.30**	1030.6	**2.83**	1030.6	**15.46**
Hargreaves-Samani	**HER**	866.0	**22.43**	865.9	**8.05**	941.1	**327.50**	945.8	**19.01**	1009.7	**2.78**	1009.7	**15.15**
Mass Transfer													
Ryan-Harleman	**ERH**	623.1	**16.14**	682.0	**6.34**	896.6	**312.01**	794.2	**15.96**	747.2	**2.05**	747.2	**11.21**
Trivett	**ETR**	261.8	**6.78**	282.7	**2.63**	488.0	**169.81**	439.0	**8.82**	368.9	**1.01**	368.9	**5.53**
Quinn	**EQN**	199.6	**5.17**	215.4	**2.00**	431.0	**149.98**	386.8	**7.78**	296.4	**0.81**	296.4	**4.45**

Evap[1]: Evaporation in terms of depth of water evaporated (mm/year).

Vol[1]: Evaporation in terms of volume of water evaporated (x 10^6 m^3/year).

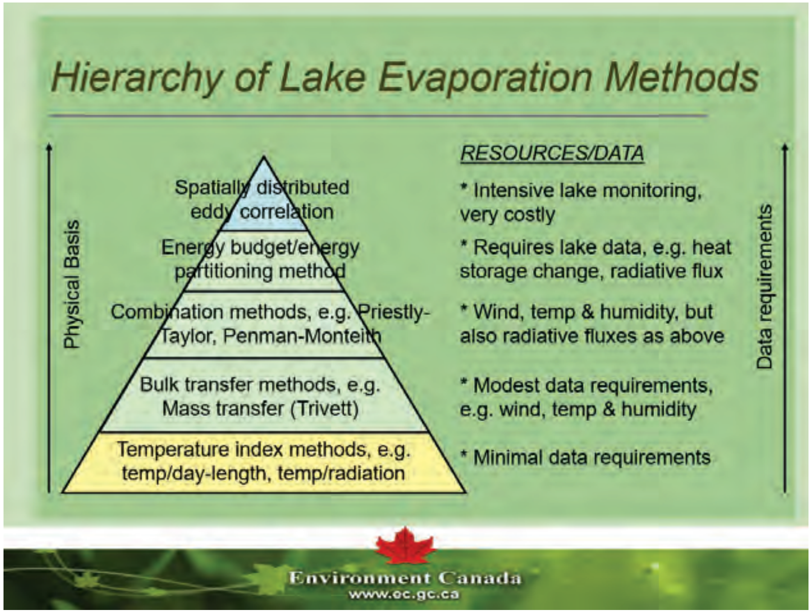


Figure 1-7 Hierarchy of lake evaporation methods based on soundness of its physical basis, versus data required by each method. This figure is reproduced from a presentation slide by Schertzer and Taylor of Environment Canada (n.d.).

Spence and Hedstrom (2015) conducted a long-awaited observational study, utilizing 3 meteorological buoys, placed at northern, central, and southern locations on Okanagan Lake, which for nearly three years (from July 2011 to May 2014, a period of normal air temperatures) measured air and water conditions at 10-minute intervals; and eddy covariance systems, installed on Coast Guard beacons at Gartrell and Manhattan Points. Air conditions were measured at 3 m above the lake surface and included barometric pressure, temperature, vapour pressure, and wind direction. Water temperature was measured at depths of 0.5 m and 2 m. The study identified the main meteorological and lake attributes that control lake evaporation, described the seasonal cycles of those variables, and estimated annual rates of evaporation from the Okanagan lakes. This study also developed a model for estimating the variation of lake surface evaporation from month to month, in response to varying atmospheric and water conditions. The authors determined that their model is reasonably accurate at the monthly time step but not reliable at the daily time step. Meteorological measurements and evaporation estimates showed significant differences between the northern, central, and southern portions of Okanagan Lake, with higher evaporation in the north due to higher water temperatures, stronger vapor pressure gradients and less atmospheric stability.

From the time series of daily evaporation estimates by Spence and Hedstrom (2015) based on data collected from July 2011 to May 2014, we calculate an average annual evaporation rate of 726 mm/year for Gartrell Point and 823 mm/year for Manhattan Point. There is considerable seasonal variation in the daily estimates (with minima in March-April and maxima in the summer months), and significant year-to-year variability (Figure 1-8). Local meteorological conditions during the data collection period were approximately average, and it seems likely that the average monthly estimates obtained from this study (Figure 1-9 and Table 1-2) are indicative of long-term historical averages.

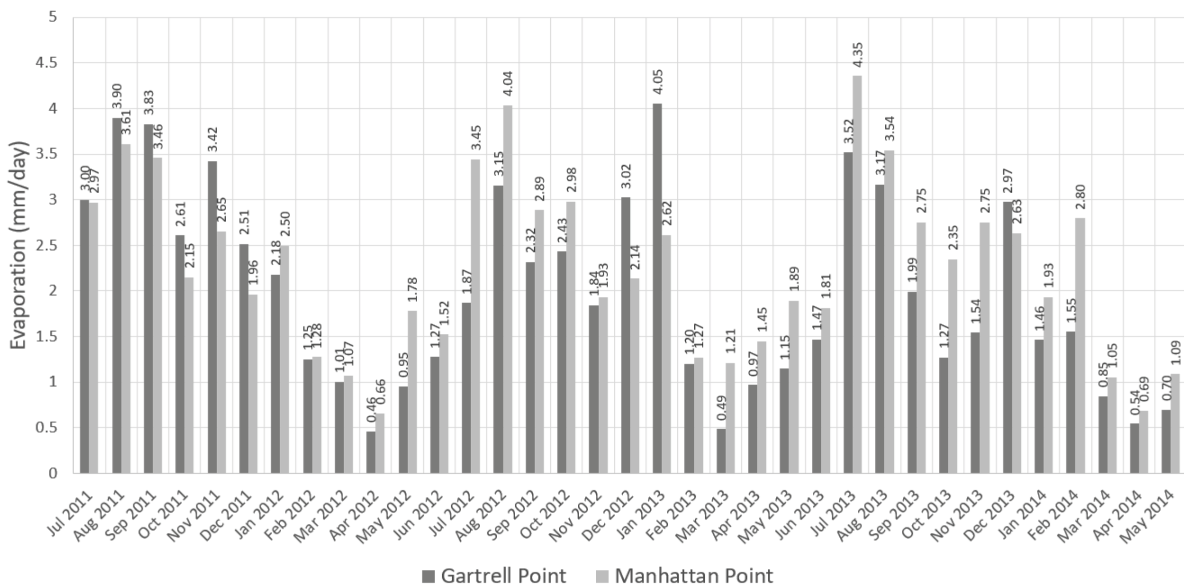


Figure 1-8 Average daily evaporation rates (mm/day) by month, for Gartrell Point (dark gray) and Manhattan Point (light gray), calculated from the Spence and Hedstrom (2015) daily time series of observations-based evaporation estimates.

Application of the most accurate methods for estimating lake evaporation requires a variety of field measurements that are not available for the Raven ORB hydrologic model. The most useful information identified in the literature for evaluating the hydrologic model's lake evaporation simulations is the observations-based daily time series obtained by Spence and Hedstrom (2015), during a period of nearly 3 years during which meteorological conditions were approximately average (Figure 1-8), and whose monthly means are shown in Figure 1-9 and Table 1-2.

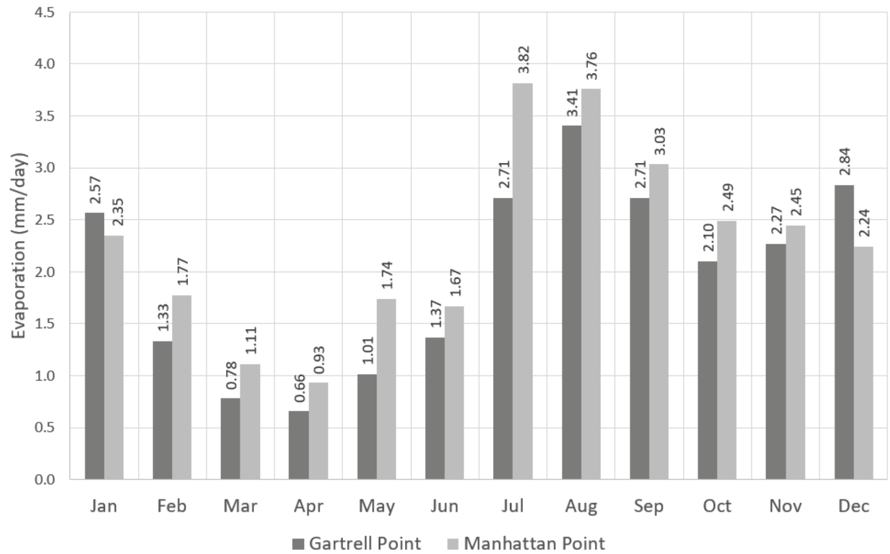


Figure 1-9 Monthly average evaporation rates (mm/day) over the period of record (July 2011 – May 2014), for Gartrell Point (dark gray) and Manhattan Point (light gray), calculated from the Spence and Hedstrom (2015) daily time series of observations-based evaporation estimates. The values plotted are also listed in Table 1-2.

Table 1-2 Average daily evaporation rate (mm/day) for Gartrell Point and Manhattan Point calculated from the daily time series by Spence and Hedstrom (2015). These data are plotted in Figure 1-9.

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gartrell Point	mm/day	2.57	1.33	0.78	0.66	1.01	1.37	2.71	3.41	2.71	2.10	2.27	2.84
	mm/mon	80	38	24	20	31	41	84	106	81	65	68	88
Manhattan Point	mm/day	2.35	1.77	1.11	0.93	1.74	1.67	3.82	3.76	3.03	2.49	2.45	2.24
	mm/mon	73	50	34	28	54	50	118	117	91	77	74	69

CHAPTER 2 CLIMATOLOGY

2.1 Chapter Synopsis

This chapter presents a brief description of the historical climate of the Okanagan and Similkameen river basins (section 2.2), the changes being brought about by regional manifestations of global warming and the hydrologic mechanisms by which atmospheric temperature and precipitation influence runoff timing, volumes and peaks are briefly introduced in section 2.3. In section 2.4, technical aspects of ECCC's climate projections data set used in this work, named the CanLEADv1 data set, are described. How these data were adjusted for use in this project are detailed in section 2.5. In section 2.6, the projected climatic changes through the end of this century are analyzed to characterize changes in temperature, precipitation, length of freezing season and snowfall.

ECCC's CanLEADv1 projections indicate large rises in the minimum and maximum atmospheric temperature of a day, and this warming is expected throughout the year, for each of the 12 months. The minimum daily temperature generally occurs at nighttime, and the maximum occurs during daytime. The projected increase in the minimum daily temperature by the end of this century is greater than 5°C in any of the months and throughout the watersheds, and the maximum daily temperature is projected to rise by 3°C or 4°C. Rises in the minimum daily temperature (Tmin) carry important consequences as they diminish the capacity of the snowpack to lose during the night the solar heat gained during the day, thus raising snowpack temperatures and promoting snowmelt.

Rising projected temperatures shorten the annual freezing period. For example, at the Silverstar Mountain snow station, by the end of this century freezing is projected to start 5 weeks later and end 8 weeks earlier on average than at present. The projections show individual snow-free years starting to occur in the 2060s at Pinaus Lake (elev. 1,000m) or Princeton (elev. 700m); and in the late 2070s to the 2080s at high-elevation locations such as Silverstar Mountain (elev. 1,839m) and Blackwall Peak (elev. 1,940m).

Precipitation totals and daily intensity are projected to increase throughout the Okanagan and Similkameen river basins in October through May. These changes accentuate the existing contrast between wetter winters and drier summers at Silverstar Mountain, Brenda Mine and Blackwall Peak; and they introduce seasonality in the currently more uniform seasonal cycle such as at Mission Creek and Greyback Reservoir. Increases in the 75th percentile are larger than increases in the median, and increases in the 90th percentile are even larger. Increases seen in the maxima are often large, especially for the winter months. Storm duration is also projected to increase in December through February.

Snowfall is projected to decline due to rising temperatures, despite projected precipitation increases. However, high-elevation locations may experience an increase in average snowfall in December and January towards the mid-century, in some cases followed by a decline from mid-century to end-century.

2.1.1 Limitations on the Climatology Component of this Study

While there is a need to provide climate projections for a variety of planning purposes, the underlying projections of climate change are subject to large and unquantifiable uncertainty. The main sources of uncertainty are unknown future emissions of greenhouse gases, uncertain response of the global climate system to increases in greenhouse gas concentrations, and incomplete understanding of regional manifestations that will result from global changes (e.g., (Hawkins and Sutton, 2010). Additional potential sources of uncertainty include the downscaling (in space and time) of global climate model outputs, the overall accuracy of the hydrologic model, and the assumptions made of unchanged future land cover and soil conditions.

The temperature and precipitation projections developed in this work should therefore be considered to be plausible representations of the future, given the best current scientific information, and do not represent specific predictions. The actual future realizations of temperature and precipitation over the Okanagan and Similkameen river basins, and the actual future stream flows in these basins will differ from the projections considered here, and their difference compared to historical climate may be greater or smaller than the differences in the projections considered. Also, the actual future volumes, peaks, and timing of streamflow inputs to Okanagan Lake and other lakes and streams will differ in unknown ways from the projections developed in this work.

2.2 Historic and Recent Climate

The Okanagan watershed lies in a high plateau of BC’s Southern Interior region, located in the rain shadow of the Coast Mountains and the Cascade mountain range. The watershed receives lower precipitation than most regions in BC, and experiences large evaporation losses during its hot summers. Estimated mean annual precipitation rates range spatially from 300-400 mm in the southern valley (e.g. about 320 mm at Osoyoos) to 800-1,000 mm at the highest plateaus (and surpassing 1,000 mm at the high-elevation Mission Creek headwaters, with a basin-wide average estimated around 600 mm (Alexander et al., 2013). The southern areas are driest, vegetated by sagebrush, perennial grasses, and cactus, while the somewhat wetter and cooler northern areas grow cedar and hemlock trees. The southern region between Oliver and the US border is classified as the Great Basin Biome.

With low average precipitation and high evaporation, the large and increasing Okanagan basin population has among the lowest water availability per capita in Canada. The annual hydrograph is dominated by the spring freshet, with April-June inflows representing roughly 90% of annual inflows to the Okanagan Lake and River system (Dobson, 2004). Inflows are low for all other seasons; hence all water uses depend on lake storage of spring snowmelt runoff.

The year-to-year variability of inflow volumes to Okanagan Lake, in particular, is of great importance to this project. Estimated annual inflows vary by more than an order of magnitude, from a minimum of 78 million m^3 in 1929 to 1.4 billion m^3 in 1997 (volumes which translate to 0.23 m to 4.12 m of lake storage) (Symonds, 2018).

2.3 Global Warming and Projected Regional Climate Change

The phenomenon of global warming manifests itself differently across global regions. The state of current knowledge of the global climate system is incorporated into computer simulation models of the global atmosphere, oceans, land and cryosphere, known as global climate models (GCMs), as well as models with smaller spatial domains covering a specific global region at greater spatial detail and better representation of topography, coastlines, and dynamic interactions between climate components, known as regional climate models (RCMs). Even though the volume of future anthropogenic greenhouse gas emissions and their atmospheric concentration are unknown, scenarios built on different plausible assumptions have been developed that lead to “representative concentration pathways” or RCPs. Global climate models are used for simulating the response from climate variables (such as temperature, precipitation, and wind at different world locations) to different RCPs. For example, RCP4.5 and RCP8.5 are two scenarios of future greenhouse gas concentrations estimated to lead to a global heat imbalance of 4.5 and 8.5 Watt/m^2, respectively, by year 2100.

The climate system is highly sensitive to small perturbations (a type of behavior termed “chaotic”) and for this reason different model runs by the same GCM and the same RCP but with slightly different initial conditions lead to different future projections. By running the same model multiple times to create an “ensemble”, any future trends in temperature, precipitation, etc., can be attributed to the RCP and represent the “climate change signal” associated with the RCP according to the specific GCM used.

The recent availability from ECCC of an ensemble of 50 runs of the Canadian GCM CanESM2 for RCP8.5, whose results were then refined (or “dynamically downscaled”) by the Canadian RCM CanRCM4, represented an opportunity for this project. Given the role of human management in the Okanagan lake system, evaluation of future flood risk cannot rely on the fitting of an extreme value distribution to a relatively short period of hydrologic simulations. Not only the hydrology but also the management behavior must be simulated for evaluating flooding risk, and since a managed system may not follow a known distribution, the project benefits from simulating a long period of time, which is possible with the approach of using an ensemble of 50 climate projections, provided by ECCC’s CanLEADv1 data set, described in the next section.

The hydrologic model (Chapter 3) translates CanLEADv1’s climatic projections of temperature and precipitation into projections of runoff through the end of this century. The hydrologic processes affected are represented schematically in Figure 2-1. Additionally, simulation of human management leads to projections of lake levels and flooding risk.

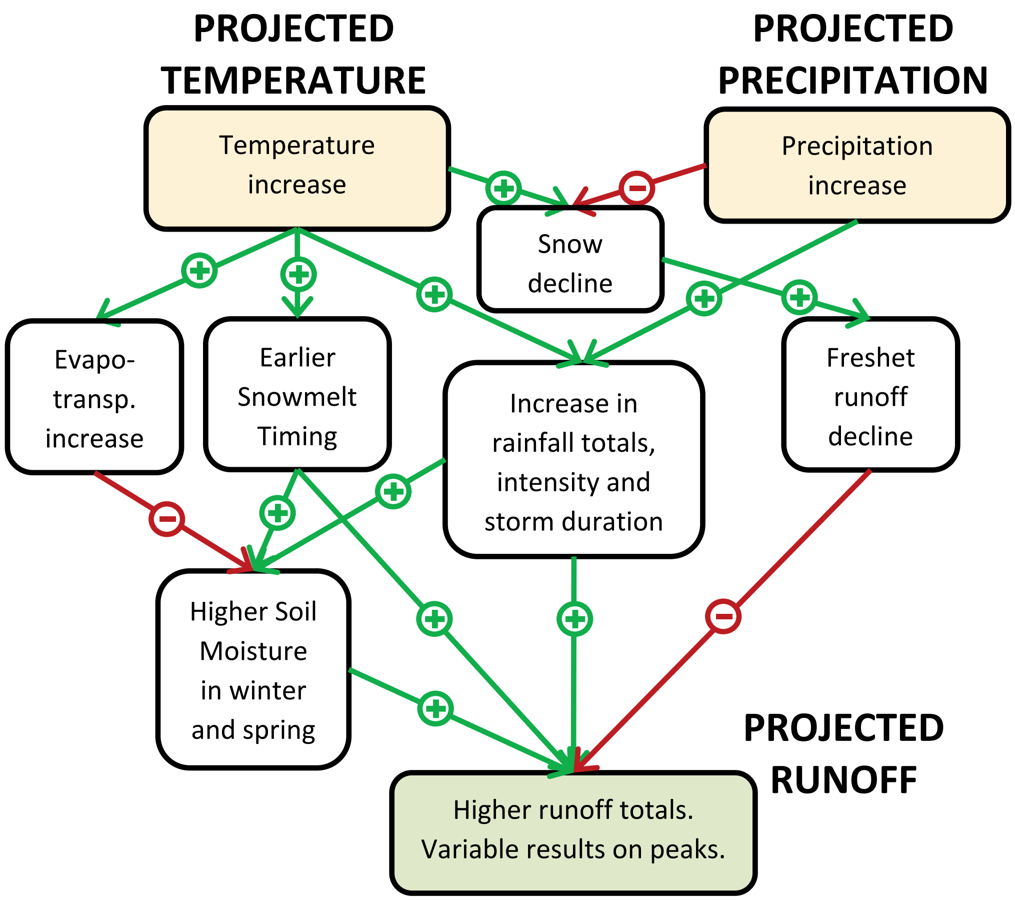


Figure 2-1 Hydrologic pathways by which projected climatic changes influence runoff in the Okanagan and Similkameen basins. Green arrows represent positive contributions towards the contents of a box, while red arrows represent opposing contributions. For example, the projected temperature increase contributes to the decline in snowfall and increase in rainfall. Opposing contributions from (a) higher rainfall totals and intensity and higher soil moisture versus (b) lower freshet runoff, result in complex impacts on runoff peaks that depend e.g. on subbasin size and elevation.

2.4 Description of Climate Ensemble

The Canadian Large Ensembles Adjusted Dataset version 1 (CanLEADv1), developed by ECCC, contains climate model simulation outputs of daily precipitation (pr), minimum daily temperature (Tmin or tasmin), maximum daily temperature (Tmax or tasmax), and other climatic variables, on a 0.5° grid covering North America. There are 50 climate model simulations forming an ensemble, from the Canadian Earth System Model Large Ensemble (CanESM2 LE)[1] for the future greenhouse gas

[1] https://open.canada.ca/data/en/dataset/aa7b6823-fd1e-49ff-a6fb-68076a4a477c, accessed 31 March 2020.

concentration pathway RCP8.5. The 50 GCM outputs were downscaled by the Canadian Regional Climate Model Large Ensemble (CanRCM4 LE). The data are adjusted statistically to remove model bias and ensure agreement with two observationally-constrained historical meteorological forcing data sets, S14FD and EWEMBI. In this project the version adjusted for S14FD was used.

2.4.1 Climate Ensemble's Global Climate Model (GCM) vs. Other GCMs

The global climate model used in the CanLEADv1 data set is CanESM2. In this section it is investigated whether CanESM2's projections for the Okanagan-Similkameen basins stand out as different from other GCM's projections. The Pacific Climate Impacts Consortium (PCIC) recommends for Western North America a list of GCM runs which are chosen to cover as wide a range as possible of differing projections[1]. This PCIC list was the basis for the selection of the five GCMs used in the Okanagan Irrigation Water Demand study (Neilsen et al., 2018). In this section those five GCM runs plus the 6th GCM run on the PCIC list are studied and compared with CanESM2 (r1). The GCM runs are listed in Table 2-1.

Statistically-downscaled projections of the seven GCM runs listed in Table 2-1 were downloaded from an archive supported by educational institutions and the U.S. government, for the grid cells shown in Figure 2-2. The CanESM2 (r1) projections in this section are not expected to agree quantitatively with those from the same model run that are part of CanLEADv1 used in this study. They agree only approximately but differ somewhat quantitatively because they were downscaled differently, and their spatial resolution is different. The CanESM2 (r1) projections used in this section, like all other GCM projections in this section, were downscaled using only statistical methods (specifically, the method known as BCCA) and have 1/8° spatial resolution (about 12 km); while CanLEADv1 uses dynamical downscaling with the regional climate model CanRCM4 followed by bias correction, and further statistical downscaling for this project to a 500 m resolution (described in section 2.5).

Because all GCM projections used in this section were downscaled by the same methodology, they are directly comparable for the purposes of determining whether CanESM2 (r1) stands out as significantly different in any of its projections. Differences between GCM runs are expected since the choice of GCM runs on PCIC's list is guided precisely by the goal of maximizing the spread of projections.

With respect to the daily minimum and maximum temperature (Tmin and Tmax), CanESM2 (r1) projects for the end of this century (year 2100) the highest warming rates among these seven GCMs, as seen in the distributions plotted in Figure 2-3 and Figure 2-4. However, the difference is not great and does not appear as an outlier run. Indeed, all seven projections appear mutually consistent. CanESM2 (r1) also projects higher precipitation increases in mean annual precipitation (by an overall 160 mm in the course of this century, i.e. 2001-2100) than any of the other GCMs studied in this section. Nevertheless, five of the other GCMs also studied project precipitation increases in this century, ranging from 43 mm for

[1] https://pacificclimate.org/data/statistically-downscaled-climate-scenarios, accessed 31 March 2020.

access1-0.1 (r1) to 104 mm for cnrm-cm5.1 (r1). Ccsm4.2 (r2), however, projects a small declining trend in precipitation, by about 40 mm in 2001-2100.

It is concluded that CanESM2 (r1) projects markedly warm and wet future conditions and it is inferred that the CanLEADv1 projections used in this study are likely warmer and wetter than would have been obtained from other GCMs. Nevertheless, the differences are not great.

Table 2-1 The seven GCM runs studied in this section.

Acronym (and run #)	GCM Name
ACCESS1-0.1 (r1)	Australian Community Climate and Earth System Simulator
CanESM2 (r1)	Canadian Earth system Model
CNRM-CM5.1 (r1)	Centre National de Recherches Météorologiques Climate Model
CSIRO Mk3.5-6-0.1 (r1)	CSIRO Mk3.5
INMCM4.1 (r1)	Institute of Numerical Mathematics Climate Model
CCSM4.2 (r2)	NCAR/UCAR Community Climate System Model
MIROC5.3 (r3)	University of Tokyo's Model for Interdisciplinary Research on Climate

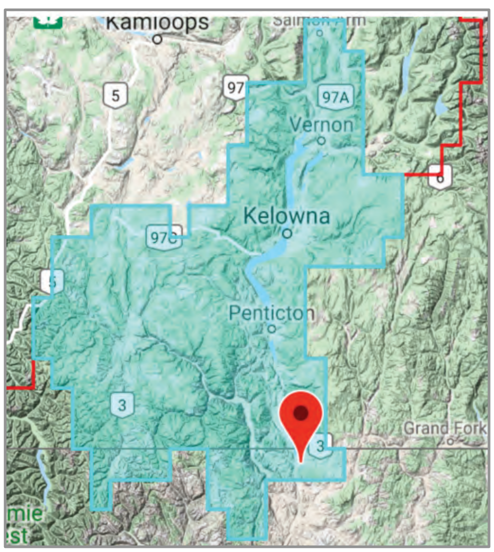


Figure 2-2 Grid cells for which downscaled projections are summarized in this section, corresponding to the watershed area defined by the indicated outlet location (latitude 50.5801°N, longitude 123.5941°E), encompassing the Okanagan and Similkameen river basins. Grid cells have a 1/8° spatial resolution, or about 12 km.

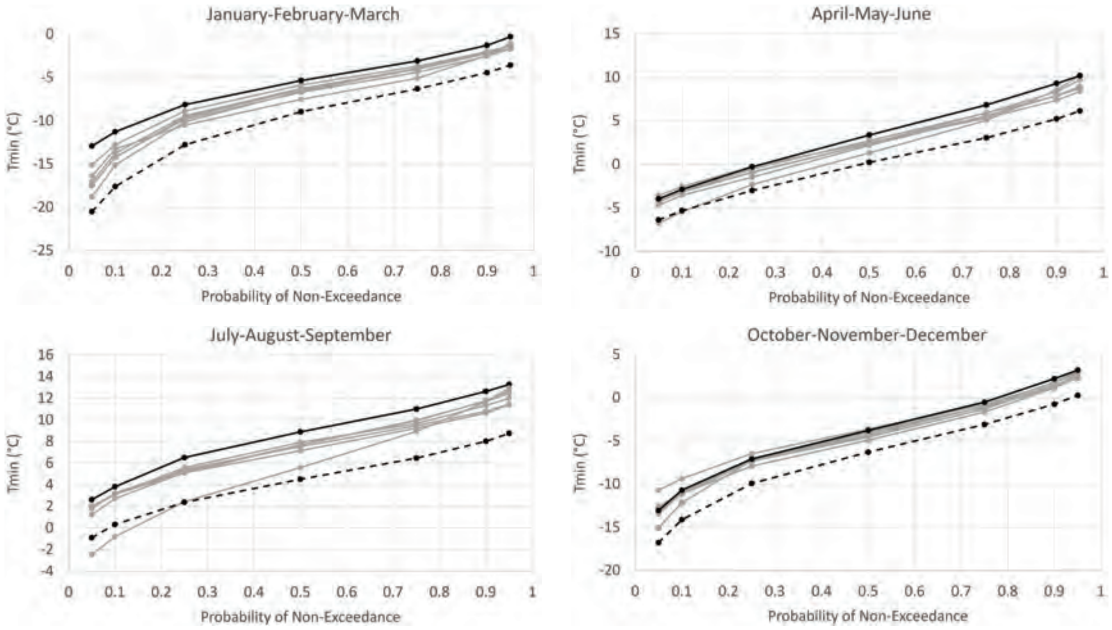


Figure 2-3 Comparison of CanESM2 (r1) projections for the end of this century (black line) for minimum temperature of the day, Tmin, against six other GCMs in Table 2-1 (grey lines). The historical period is represented by the dashed black line. These CanESM2 projections differ from those used in this study, as they belong to the same dataset as the other six GCM projections, which is necessary for direct comparison (see text).

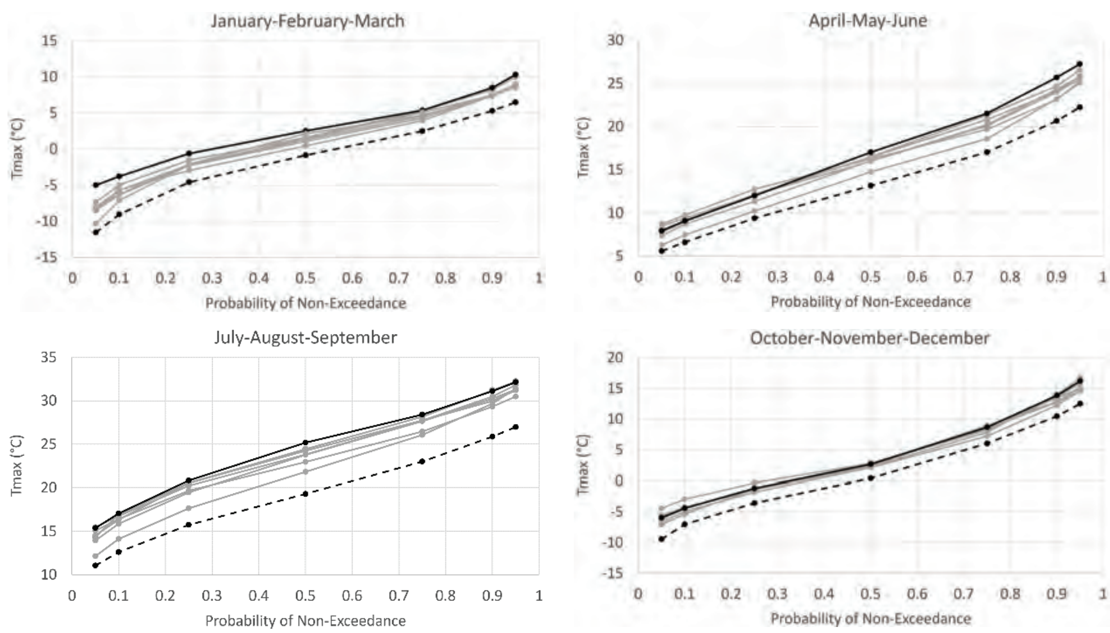


Figure 2-4 Comparison of CanESM2 (r1) projections for the end of this century (black line) for maximum temperature of the day, Tmax, against six other GCMs in Table 2-1 (grey lines). The historical period is represented by the dashed black line. These CanESM2 projections differ from those used in this study, as they belong to the same dataset as the other six GCM projections, which is necessary for direct comparison (see text).

2.5 Downscaling of the Climate Ensemble to the Okanagan and Similkameen Basins

The spatial resolution of the CanLEADv1 data set is 0.5° of latitude and longitude (or about 55 km x 37 km), and the temporal resolution is 3-hourly. A much finer climatic projections dataset was desired by OBWB for this project as well as future envisioned projects. The desired spatial resolution is 500 m and the desired temporal resolution is daily. The desired data set was developed using statistical downscaling methods.

2.5.1 Developing an Observations-Based Climate Dataset

Statistical downscaling methods rely on a target dataset of gridded values of each climatic variable derived from observations. Observations-based climatic datasets appropriate for use in Canada (namely, NRCanmet and ClimateBC) were not eligible because they do not extend into the United States. Instead, (Associated Environmental, 2019a, 2019b) used a combination of two data sets: (a) the spatially coarse-resolution (1/12°) but daily-scale PNWNAmet dataset[1] developed by PCIC (Werner et al., 2019), which spans 1945-2012, and (b) a spatially high-resolution (500 m) but monthly-scale dataset developed by

[1] https://www.pacificclimate.org/data/daily-gridded-meteorological-datasets, accessed 31 March 2020.

Associated Engineering using the ClimateNA[1] tool in conjunction with a 500 m DEM that covers the Okanagan and Similkameen watersheds. This methodology was proposed by Sobie and Murdock (2017). The result was a daily observations-based gridded climatological data set covering 1945-2012 at 500 m resolution. This data set inherited the BC Albers projection from the 500 m DEM. An example, corresponding to precipitation intensities for a particular day, is shown in Figure 2-5.

[1] https://sites.ualberta.ca/~ahamann/data/climatena.html, accessed 31 March 2020.

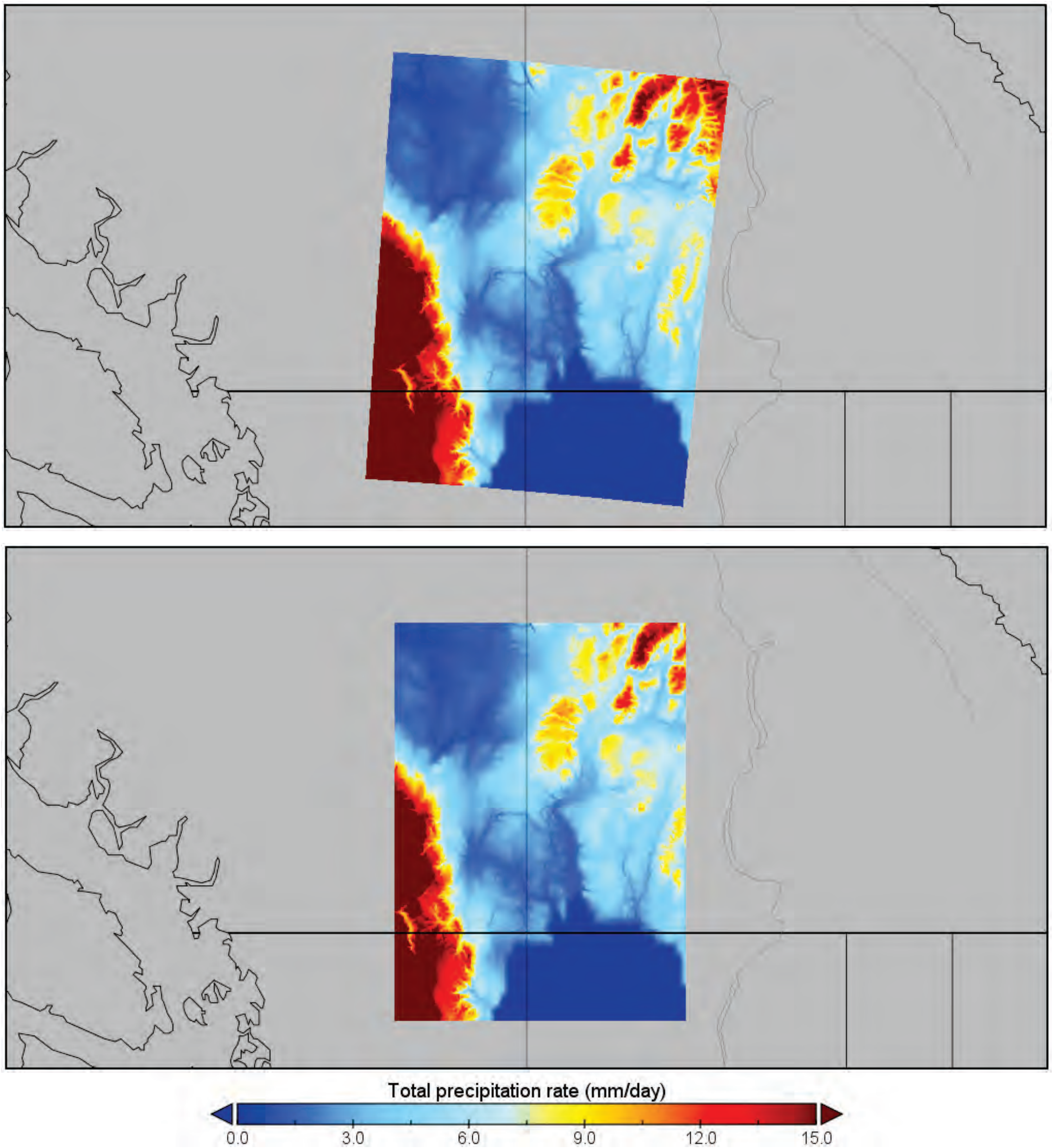


Figure 2-5 Precipitation rates on example day January 4, 1945 in the original grid provided by AE (top panel) and resampled to a regular lat-lon grid (bottom panel). The three climatic variables, pr, tasmin and tasmax were resampled in this way.

2.5.2 Downscaling Process

The spatial resolution of the CanLEADv1 (55 km x 37 km) data set is much larger than the desired 500 m, with grid cell area differing by 4 orders of magnitude. For statistically downscaling of the CanLEADv1 data to the desired 500 m resolution based on the observations-based data set described in section 2.5.1, the code ClimDown developed by the PCIC in the R language was used. ClimDown includes two alternative algorithms, bccaq and qdm. With its emphasis on extreme value representation and achieving realistic spatial patterns, bccaq was our first candidate. However, unrealistic spatial patterns of precipitation were produced, possibly due to the great difference between the original and target spatial scales.

Algorithm qdm (quantile delta mapping) performed better, producing spatially coherent spatial patterns during days with significant precipitation. In some days that had only light precipitation, data artifacts were noted where a drizzle (low-intensity precipitation) marks the grid lines of the CanLEADv1 grid, but such effects are not consequential, and the qdm algorithm was used in this project for both precipitation and temperature (Tmin and Tmax) downscaling. Figure 2-6 shows one day as an example of the qdm algorithm performance.

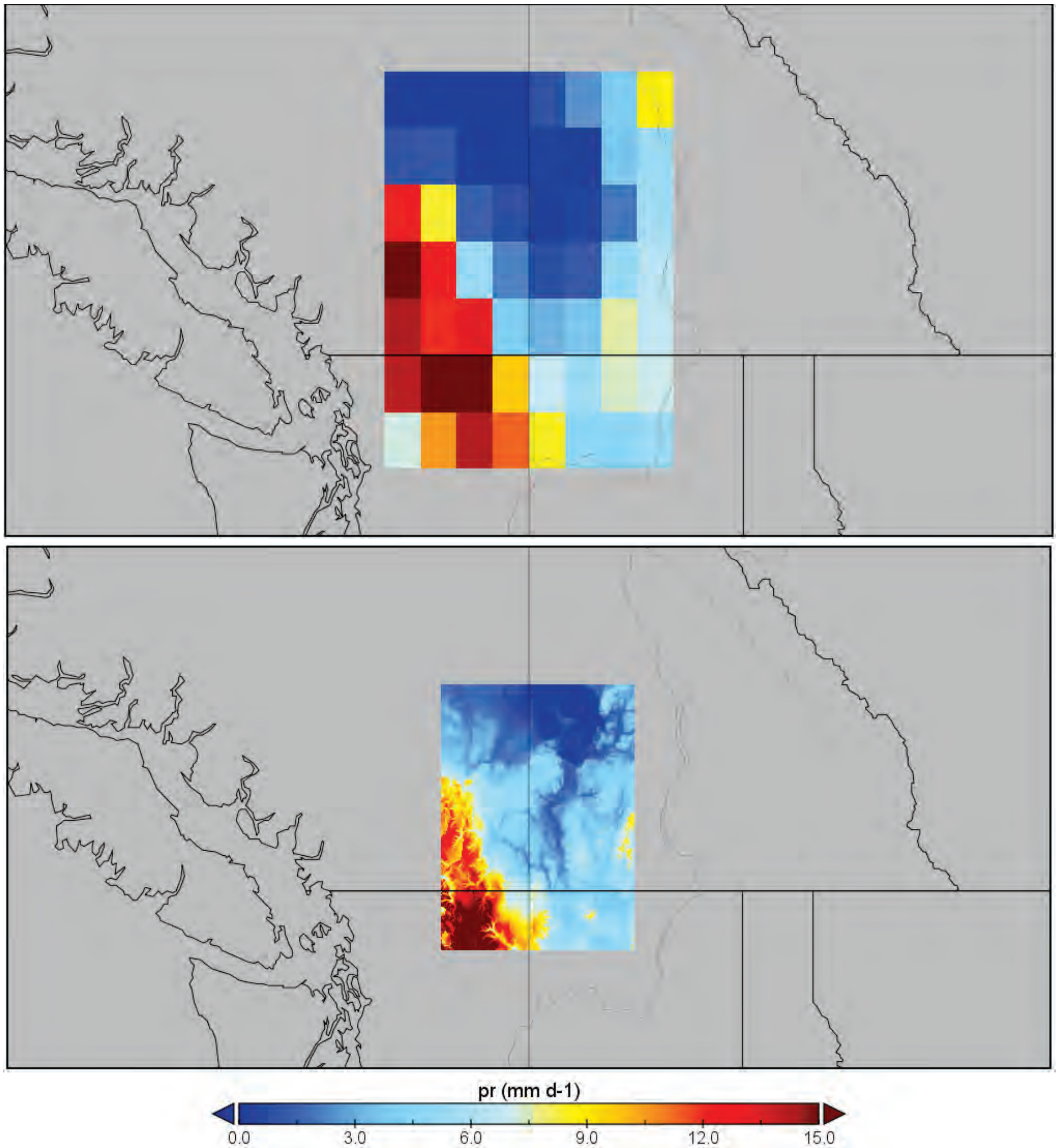


Figure 2-6 Precipitation rate in the original CanLEADv1 data set (top panel) and statistically downscaled by the qdm algorithm of the ClimDown code (bottom panel).

2.6 Assessing Projected Changes in Climate

This section describes the projected changes in climate for representative Okanagan and Similkameen locations (shown in Figure 2-7) ranging in their geographic and climatic conditions and including key snow stations and rain gauges. The projections shown correspond to the CanLEADv1 downscaled 50 realizations which are pooled together.

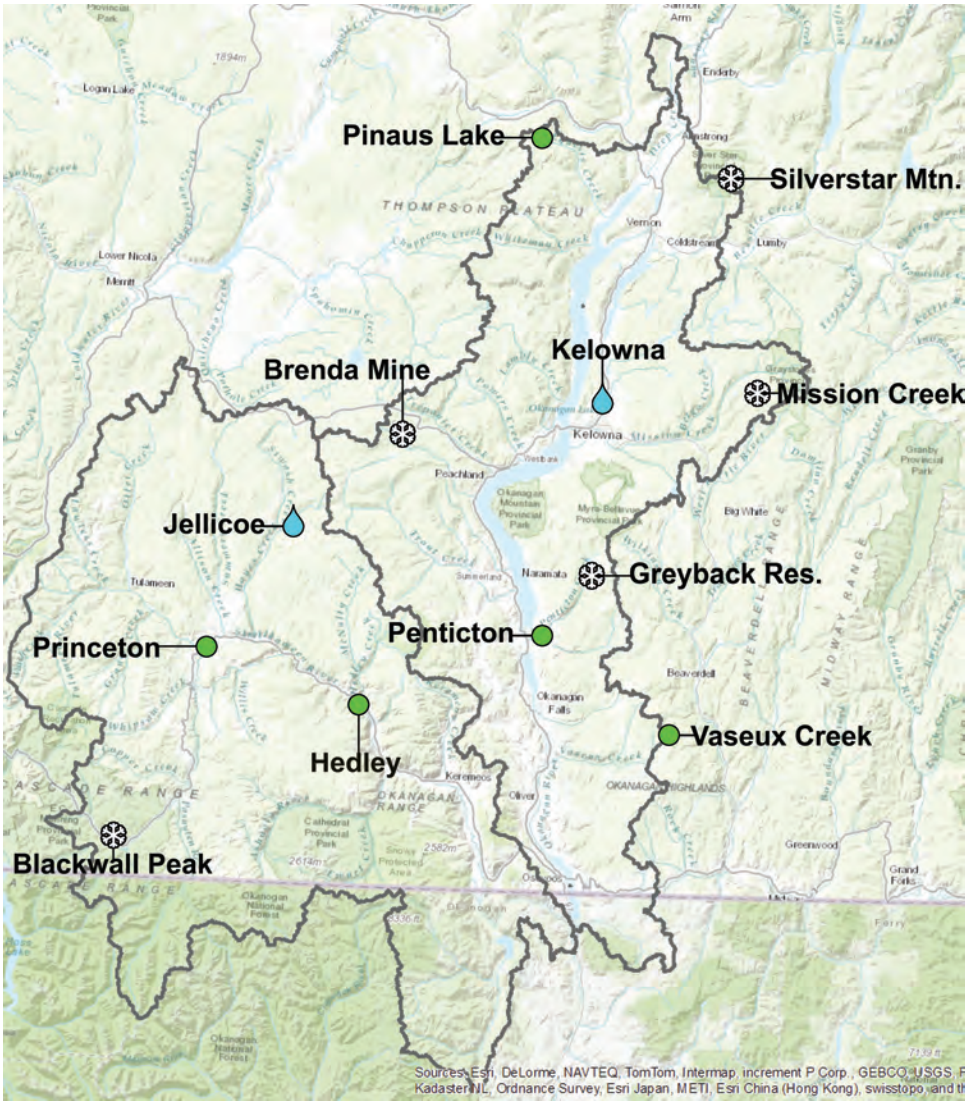


Figure 2-7 Representative locations studied in this section. Snow stations and rain gauges are indicated by a snowflake and blue drop symbol, respectively. Other locations are marked with a green dot.

2.6.1 Temperature and Freezing Season Duration

Temperature projections for representative locations are displayed in Figure 2-8 through Figure 2-10 for the daily minimum temperature (Tmin, normally occurring at night time) and in Figure 2-11 through Figure 2-13 for the daily maximum temperature (Tmax, occurring at day time). All boxplots in this chapter indicate the median (central horizontal line), the 25th and 75th percentiles (lower and upper box boundaries), and the 10th and 90th percentiles (whiskers). Color indicates the decade, from 2001-2010 through 2091-2100.

Large increases in Tmin and Tmax are projected for each of the 12 months, with Tmin rising by more than 5°C but less than 10°C in every month, and Tmax rising by 3°C or 4°C by the end of this century. Rises in Tmin carry important consequences as they diminish the capacity of the snowpack to lose during the night the solar heat gained during the day, thus raising snowpack temperatures, and promoting snowmelt.

Rising projected temperatures shorten the annual freezing period. This is shown in Figure 2-14 where the freezing period length is indicated by the red line, which represents the distance in days between the grey line (start of the freezing period) and the black line (end of the freezing period). Freezing period is defined by a mean daily temperature below 0°C. The curves represent annual averages for the downscaled 50 realizations of CanLEADv1. Given year-to-year variability, individual years in each realization differ from the average of the 50 realizations. This is shown for selected locations in Figure 2-15, where some freeze-free years are also seen, even at high-elevations such as Silverstar Mountain and Blackwall Peak, and especially at lower-elevations such as Penticton.

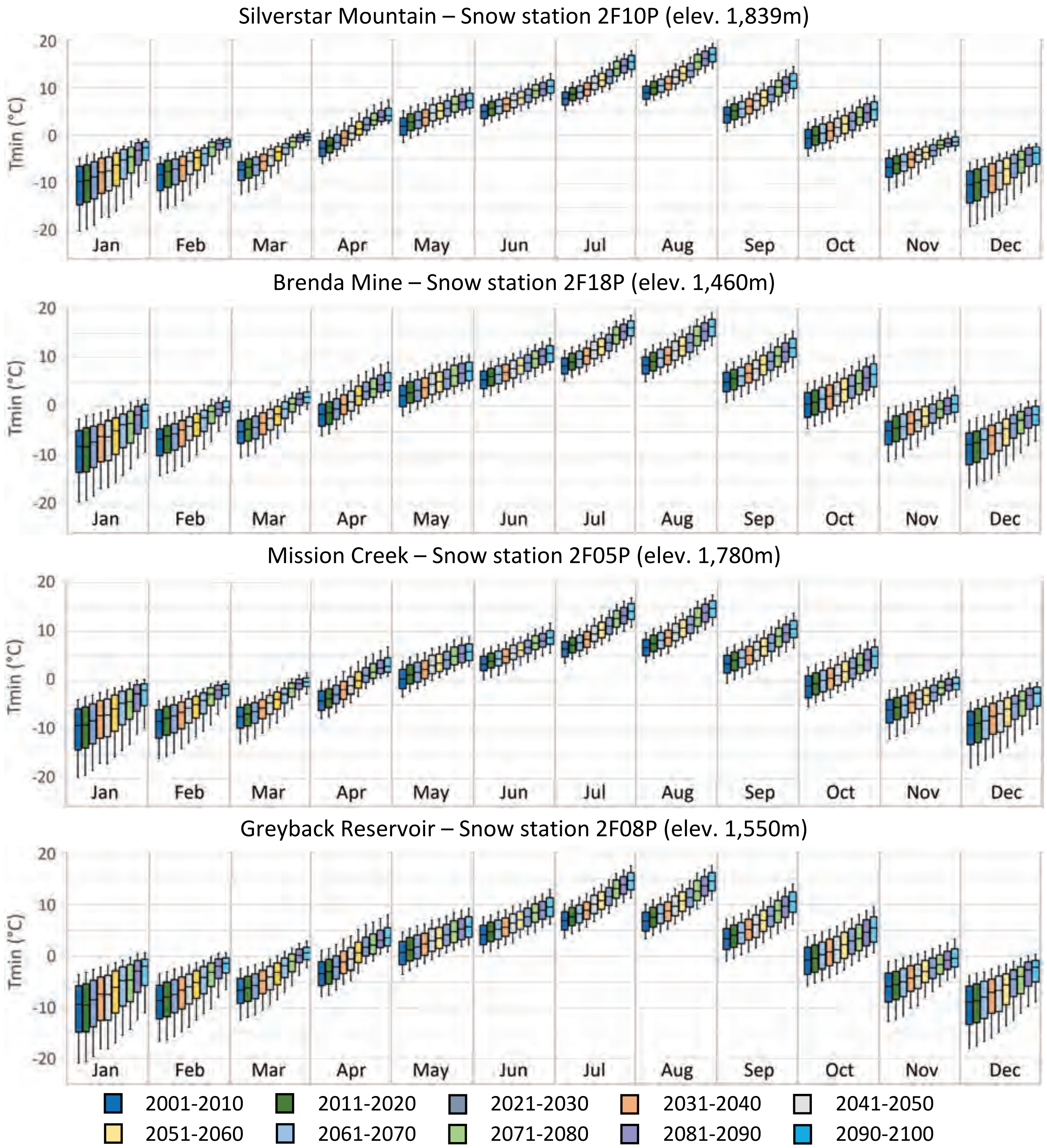


Figure 2-8 Statistical distribution of projected daily minimum temperature, Tmin, in each decade for four snow stations in the Okanagan basin.

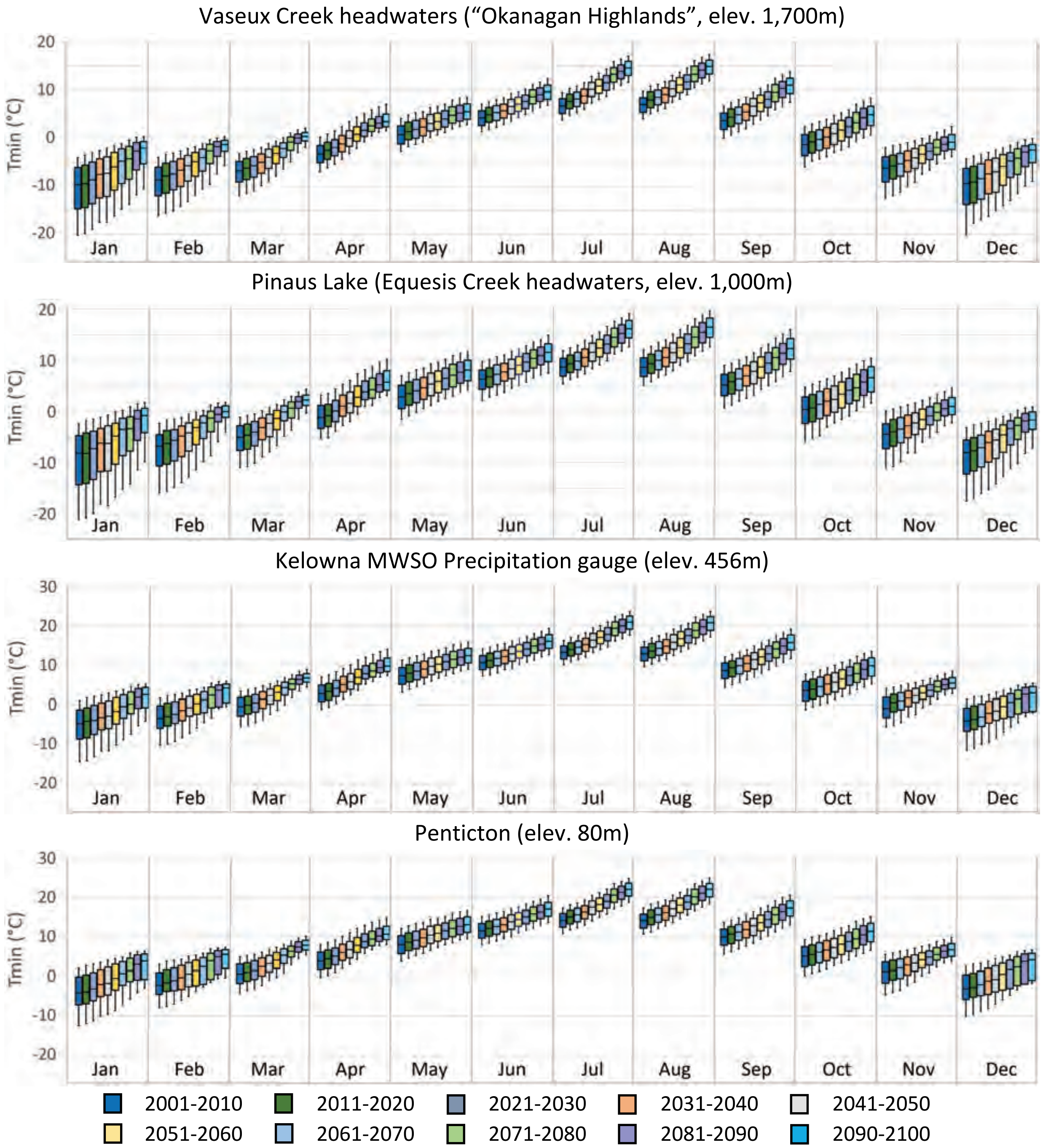


Figure 2-9 Statistical distribution of projected daily minimum temperature, Tmin, in each decade for four representative locations in the Okanagan basin, covering a range of elevations.

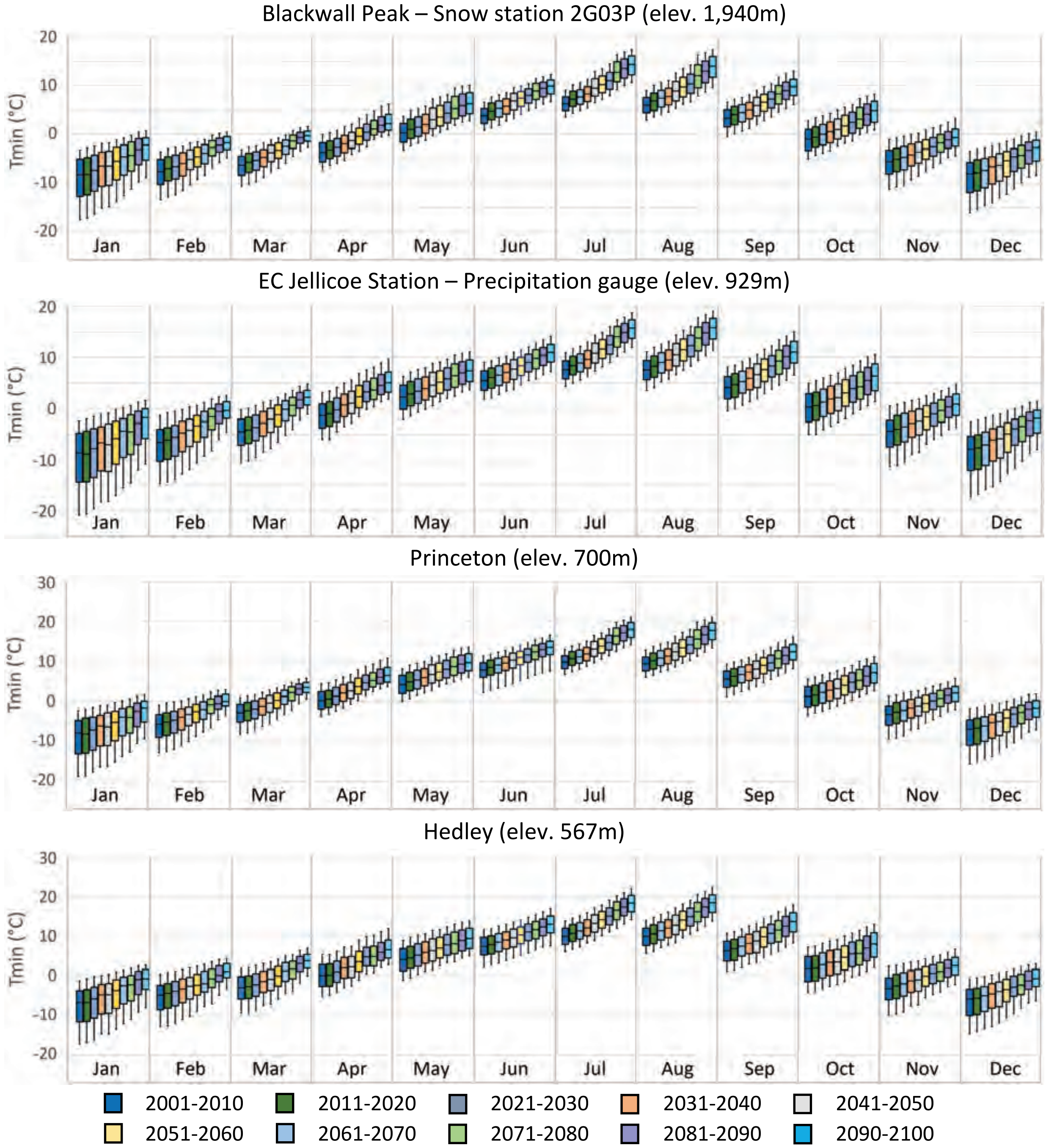


Figure 2-10 Statistical distribution of projected daily minimum temperature, Tmin, in each decade for four representative locations in the Similkameen basin, covering a range of elevations.

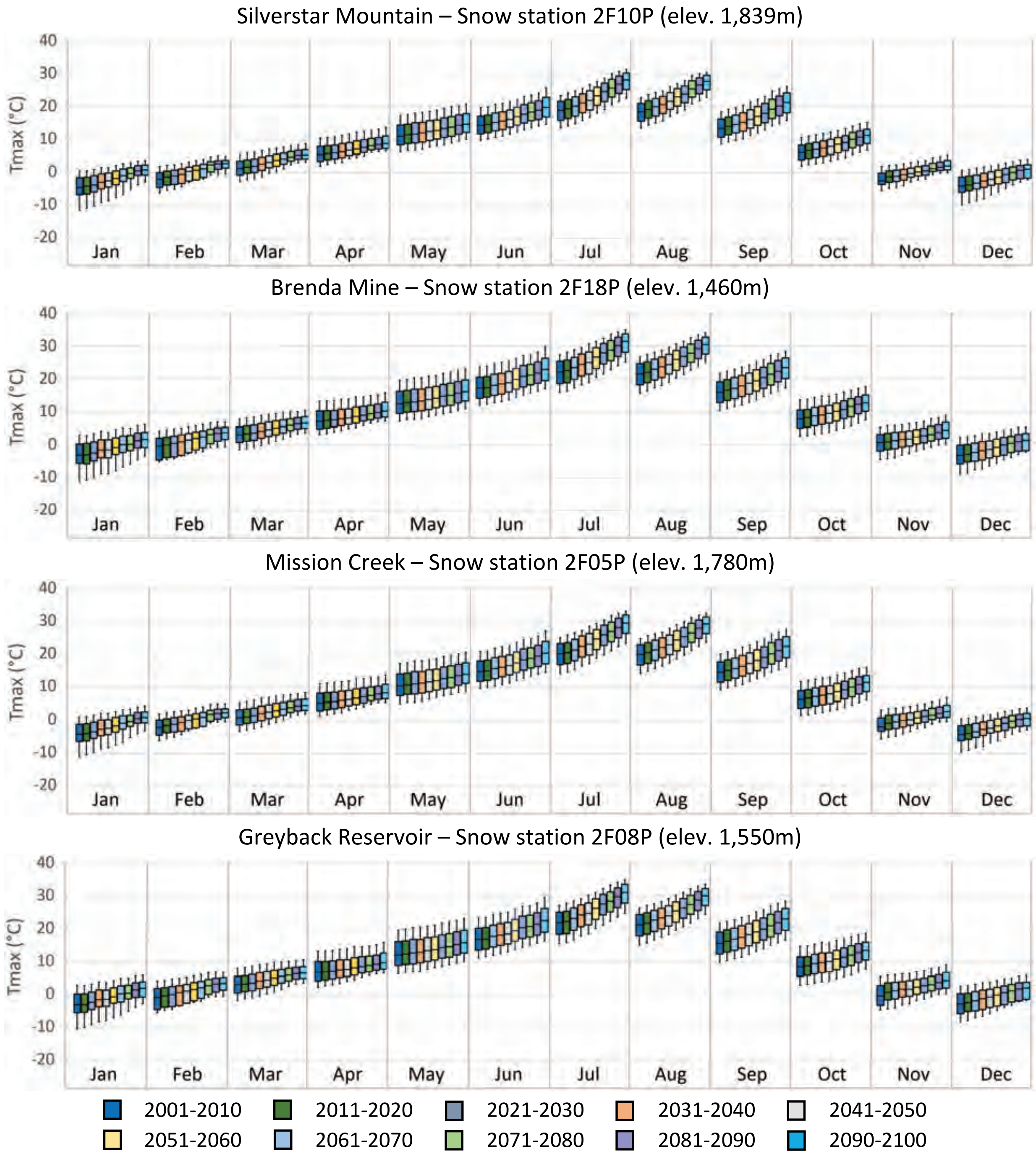


Figure 2-11 Statistical distribution of projected daily maximum temperature, Tmax, in each decade for four snow stations in the Okanagan basin.

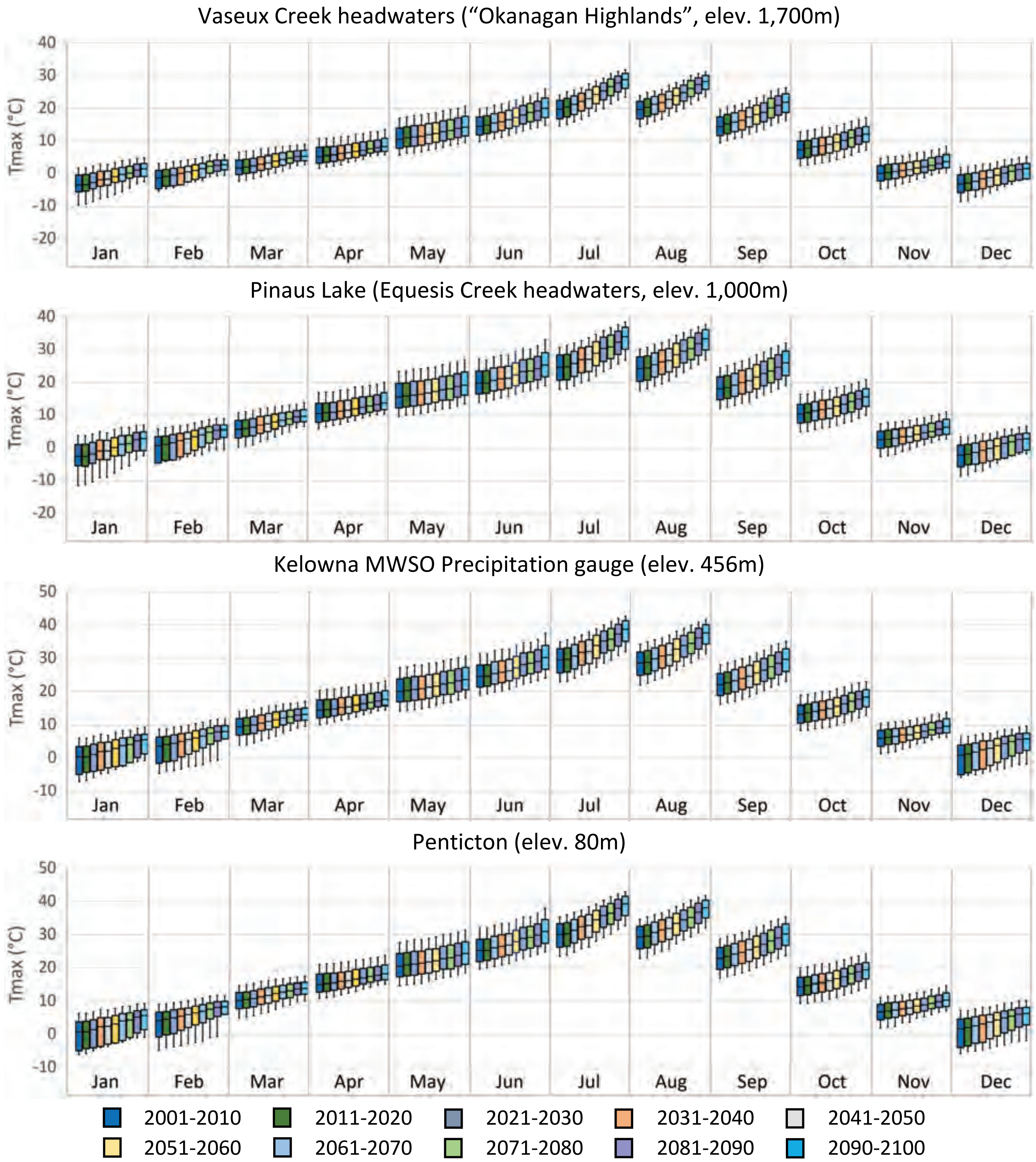


Figure 2-12 Statistical distribution of projected daily maximum temperature, Tmax, in each decade for four representative locations in the Okanagan basin, covering a range of elevations.

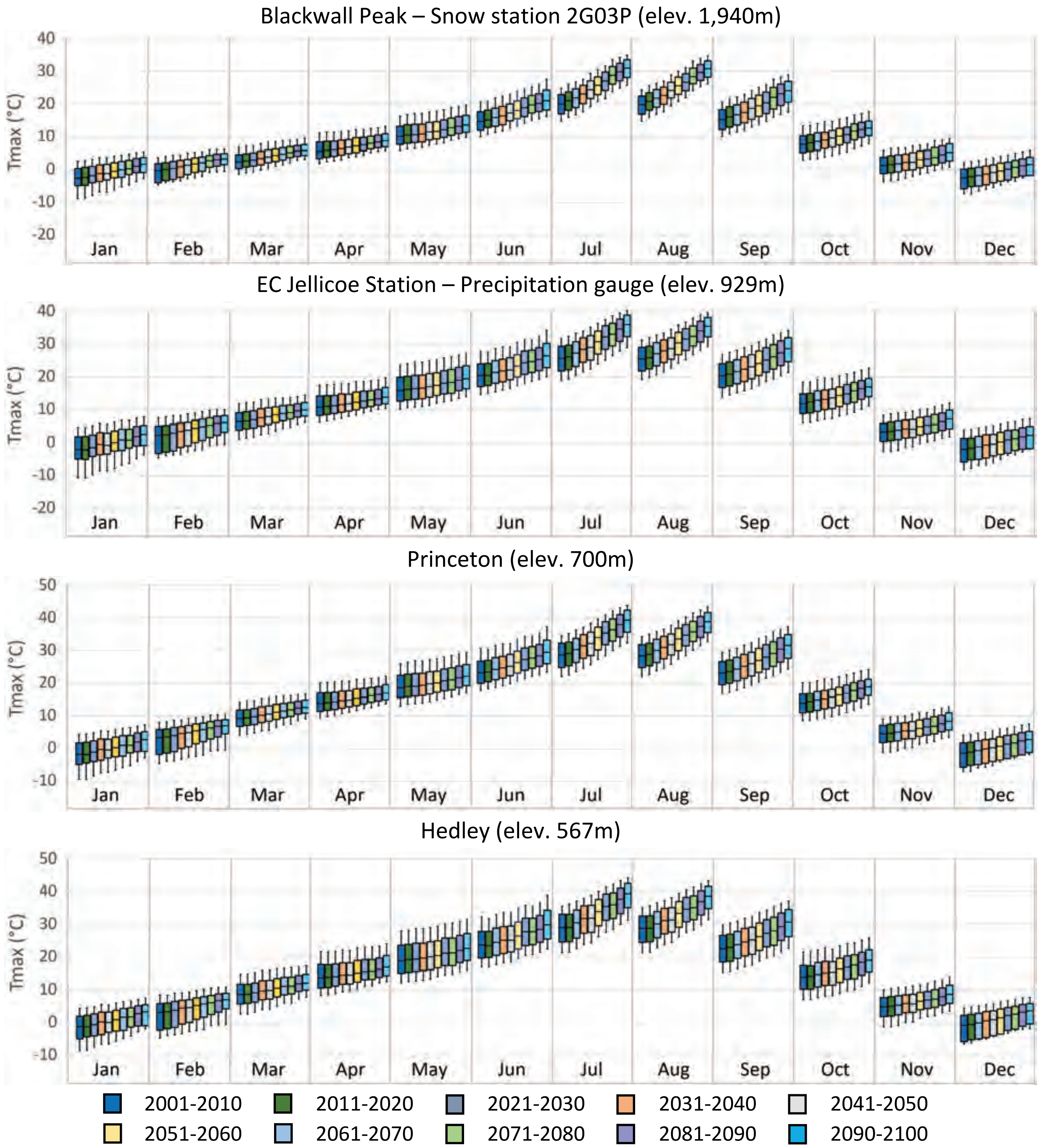


Figure 2-13 Statistical distribution of projected daily maximum temperature, Tmax, in each decade for four representative locations in the Similkameen basin, covering a range of elevations.

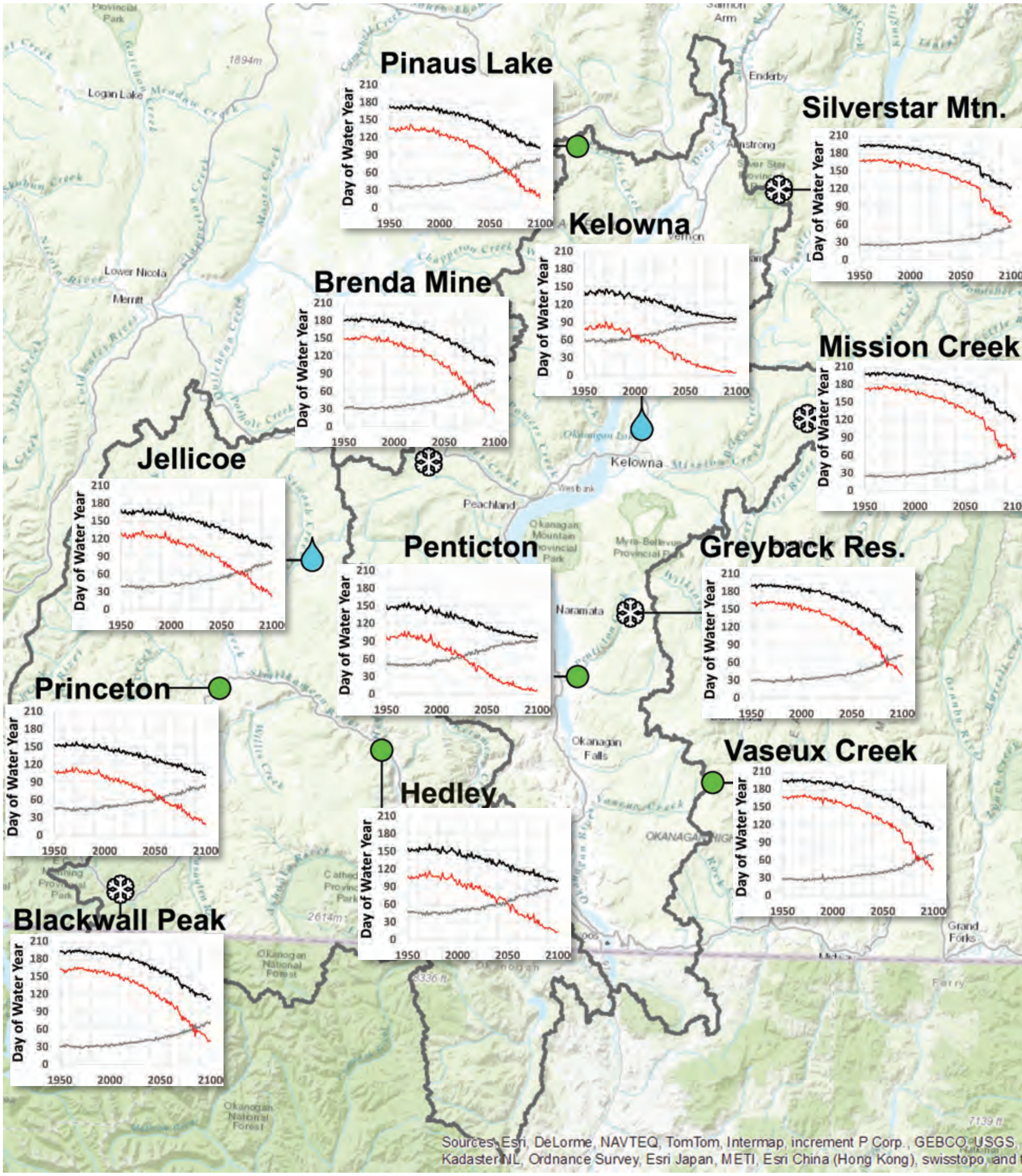


Figure 2-14 Start of the freezing period (grey line), end of the freezing period (black line) and duration of the freezing period (red line, expressing the number of days separating the grey and black lines). Freezing period is defined by sub-zero (<0°C) daily mean temperatures. The curves represent annual averages for the downscaled 50 realizations of CanLEADv1.

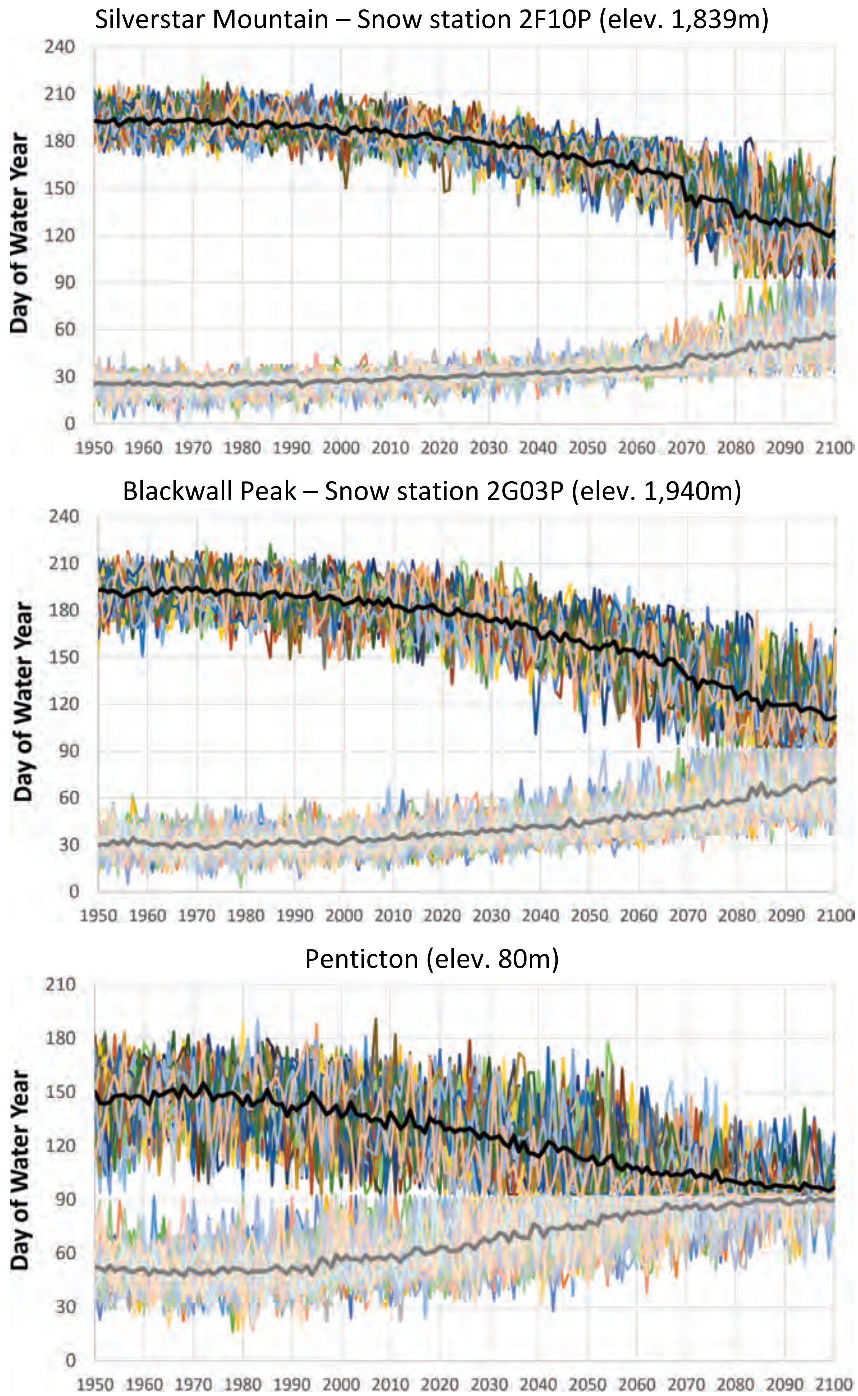


Figure 2-15 Start and end date of the freezing season. Each of the 50 climate model realizations is plotted in color. The average date of freezing season start in each year is represented by the thick grey line; the average date of end of the freezing season is represented by the thick black line. The freezing season's duration declines over time, due to a trend toward later starting dates and earlier ending dates (the latter trend being especially strong).

2.6.2 Precipitation, Snowfall, Rainfall Intensity, and Storm Duration

Precipitation is also projected to increase. Figure 2-16 through Figure 2-18 display the projected changes in the statistical distribution of daily precipitation for each of the 12 months and each decade of the 21st century, at representative locations. The distribution includes all 50 CanLEADv1 realizations pooled together. The boxplots summarize the statistical distribution by marking the median (central horizontal line), the 25th and 75th percentiles (lower and upper box boundary), and the 10th and 90th percentiles (whiskers). Hovering above the boxplots are plotted the maxima, i.e., the largest daily precipitation value of the decade.

At all locations in Figure 2-16 through Figure 2-18, significant precipitation increases are projected for October through May. These changes accentuate the existing contrast between wetter winters and drier summers at Silverstar Mountain, Brenda Mine and Blackwall Peak; and they introduce seasonality in the historically more uniform seasonal cycle such as at Mission Creek and Greyback Reservoir. Increases in the 75th percentile are larger than increases in the median and increases in the 90th percentile are even larger. Increases seen in the maxima are often large, especially for the winter months.

In Figure 2-19, the grey lines represent, for each month, the average rainstorm duration across the decades of the 21st century, while the funnel plots represent the distribution of values. Duration is the number of consecutive days with rain, calculated from daily rainfall, hence having the minimum value of 1 day. The average duration is in the vicinity of 2 days for all months. Increases in the rainstorm duration is apparent in the figure for winter months December, January, and February. The width of the funnel plots is proportional to the number of occurrences, which is greatest for 1 day, followed by 2 days, etc. All 50 realizations of downscaled CanLEADv1 were pooled together. The points highlight the maximum value simulated by any of the 50 realizations in each decade.

Snowfall is projected to decline due to rising temperatures, despite projected precipitation increases. However, high-elevation locations may experience an increase in average snowfall in December and January towards the mid-century, in some cases followed by a decline from mid-century to end-century. This can be seen in Figure 2-20.

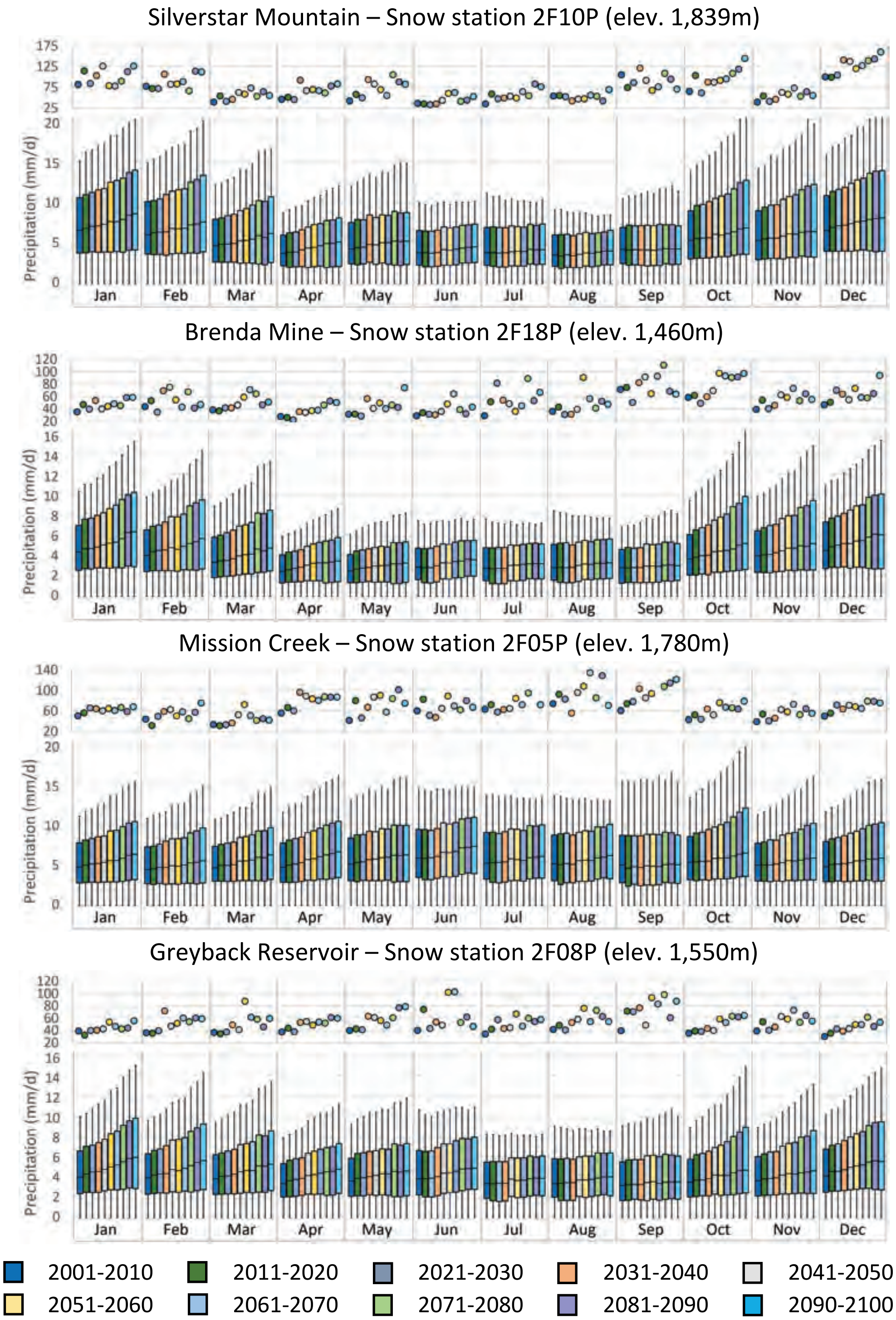


Figure 2-16 Statistical distribution of projected daily precipitation in each decade for four snow stations in the Okanagan basin. The vertical axis scale is different for the plots of maximum points above the boxplots.

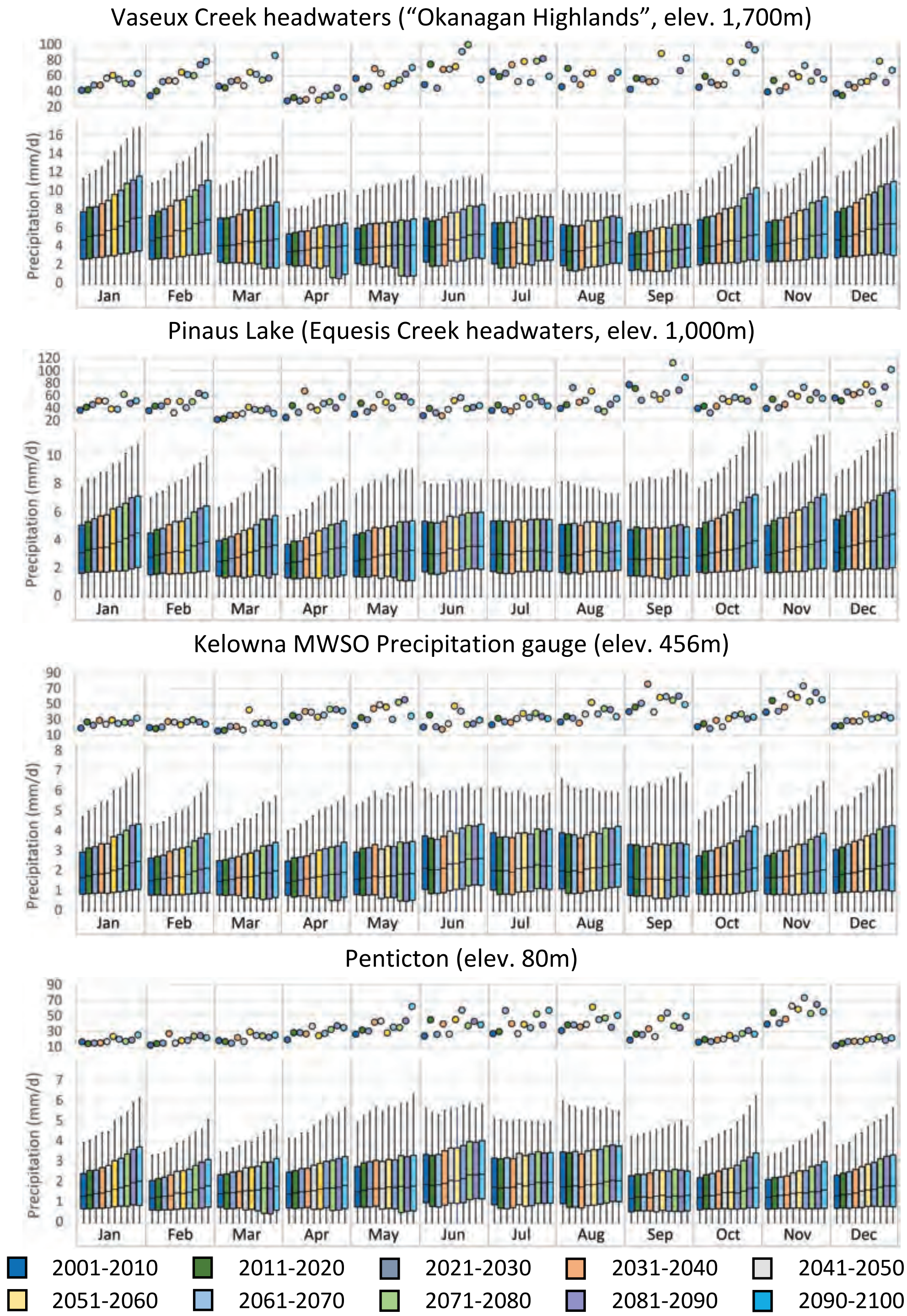


Figure 2-17 Statistical distribution of projected daily precipitation in each decade for four representative locations in the Okanagan basin, covering a range of elevations. The vertical axis scale is different for the plots of maximum points above the boxplots.

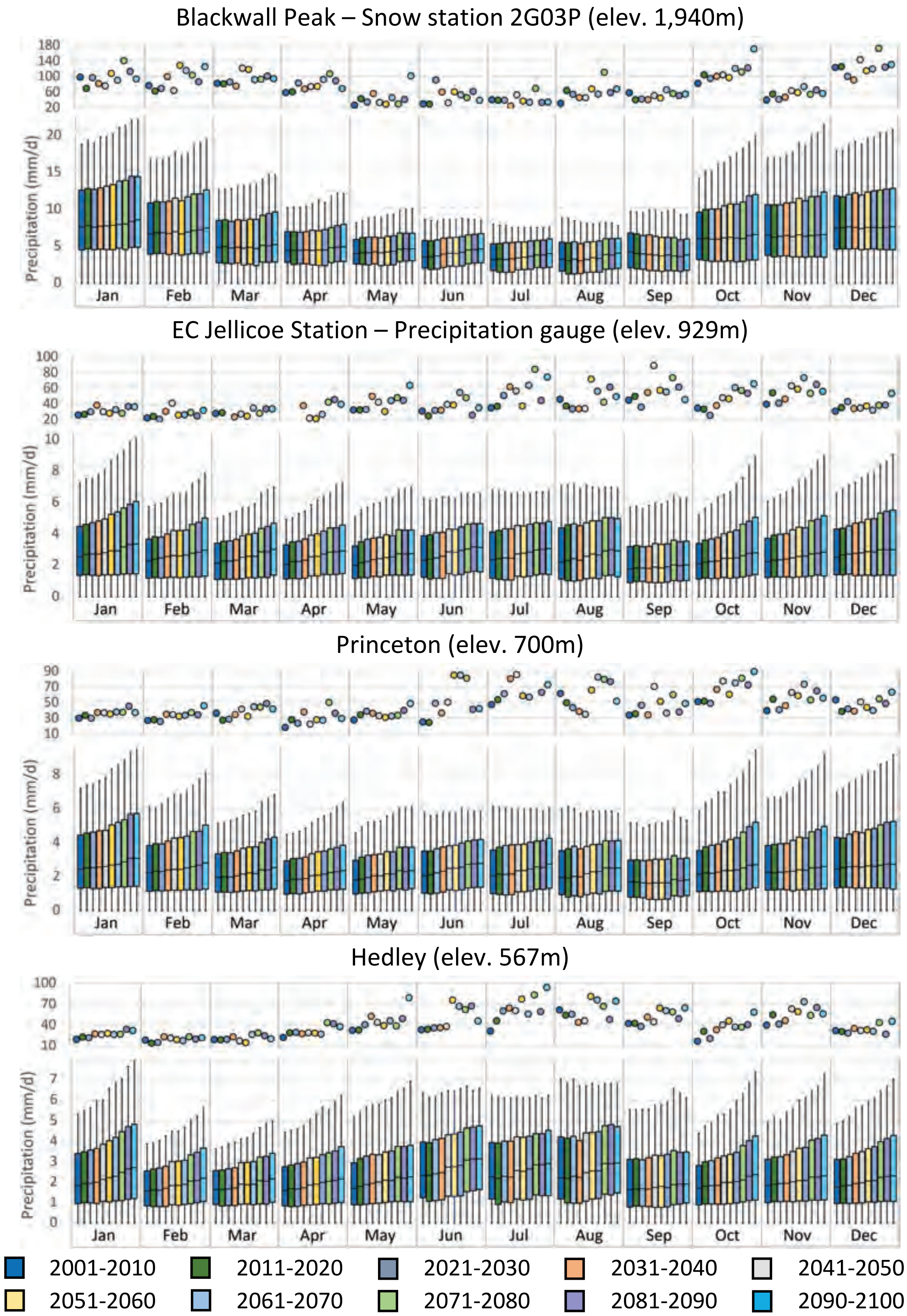


Figure 2-18 Statistical distribution of projected daily precipitation in each decade for four representative locations in the Similkameen basin, covering a range of elevations. The vertical axis scale is different for the plots of maximum points above the boxplots.

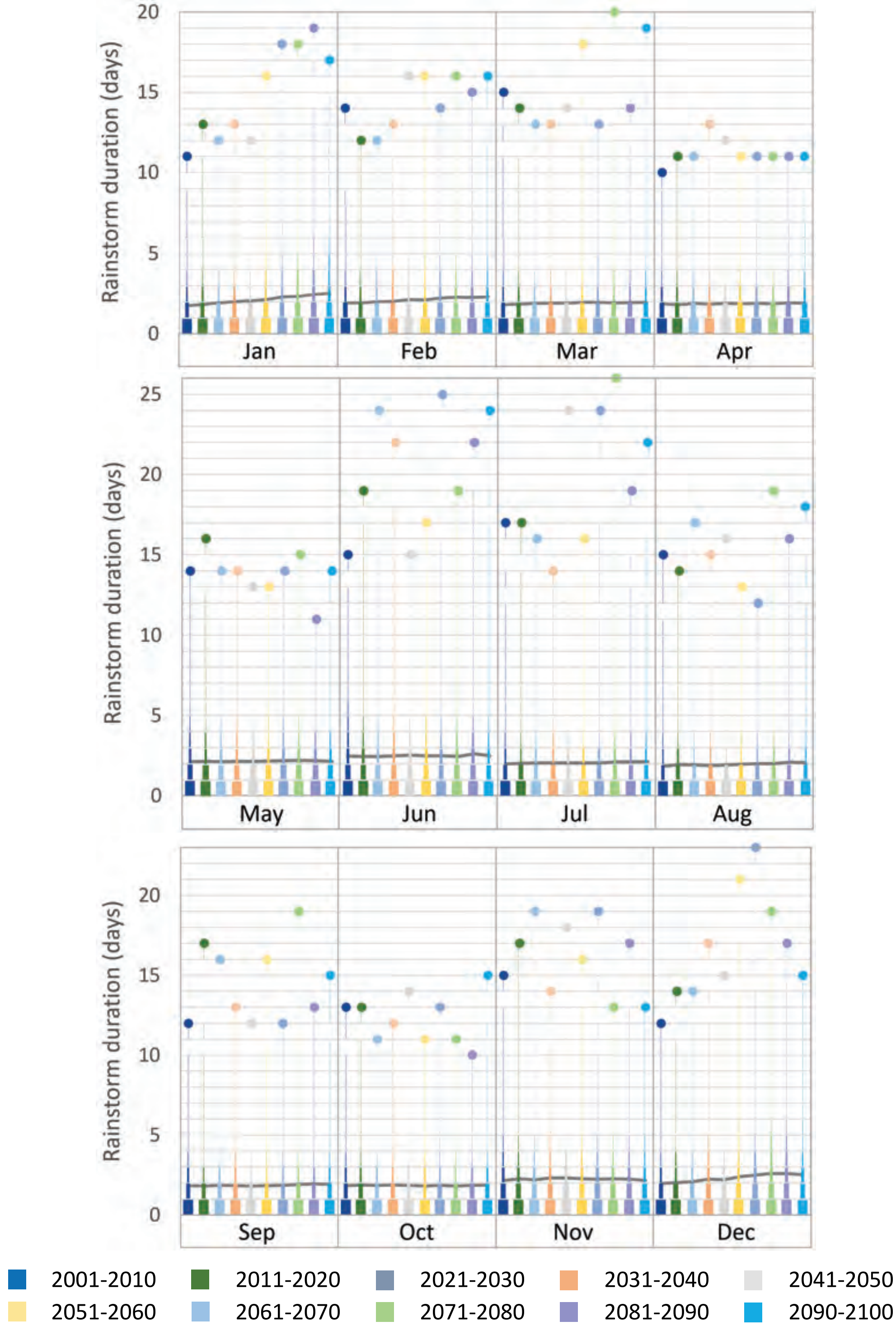


Figure 2-19 Distribution of rainstorm duration per month and decade. The grey line represents the average duration, while the funnel plots show the distribution of values and the points mark the maxima.

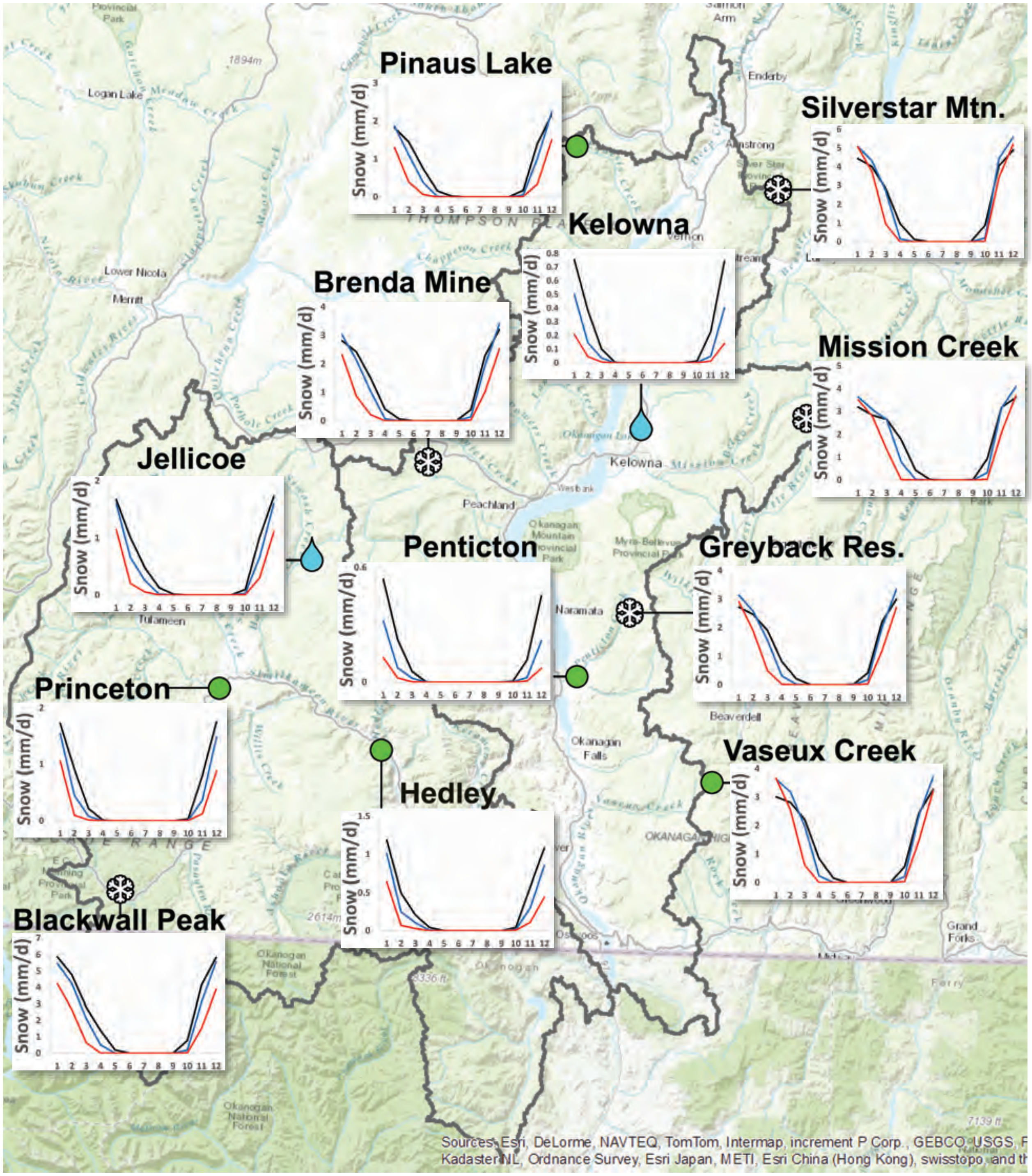


Figure 2-20 Average monthly snowfall, in mm of water equivalent per day, in decade 2001-2010 (black line), 2051-2060 (blue line) and 2091-2100 (red line).

CHAPTER 3 HYDROLOGY

3.1 Chapter Synopsis

This Chapter covers the hydrology of the Okanagan River Basin (ORB) including:

- characterizing the 2017 flood event
- what data was collected and how it was processed
- how the hydrologic model was developed, calibrated, and validated
- how backwater from the Similkameen river impacts Osoyoos Lake Levels
- how a changing climate was considered

The 2017 flood in the Okanagan River Basin (ORB) was the largest event on record on Okanagan Lake and Kalamalka Lake and produced notable flooding in other portions of the basin. The 2017 flooding was likely so significant due to the large amount of runoff volume experienced over a shorter duration than normal and earlier in the freshet. This large inflow volume was the result of significant late season snowpack combined with rapid melt and heavy spring rainfall. A motivator for this project was to determine if flooding of this nature should be expected to become more common in the future as the climate of the ORB changes. The most appropriate way to investigate this question was through a combined hydrologic and reservoir operations model of the ORB.

A large amount of data was collected in support of this goal, including spatial data describing surficial basin characteristics, bathymetric data, hydrometric data, and snow course data. The hydrologic model was developed using the Raven Hydrologic Modeling Framework (Craig and the Raven Development Team, 2019). Raven is a flexible hydrologic modelling tool that allows the user to select appropriate hydrologic algorithms and complexity.

The Raven model was calibrated manually first by examining basin level questions of overall water balance. The basin was then automatically calibrated to three unregulated subbasins using the Ostrich calibration software (Matott, 2017). Reservoir operations were also included in the model. The model operations needed to be consistent for the entire simulation period despite the fact that the regulations have changed over time. To simplify and properly represent the complicated operations in the hydrologic model, NHC worked closely with FLNRORD operators and developed three model regulation configurations.

Once the model was finalized, 50 climate ensembles from ECCC's CanLEADv1 climate projections (section 2.4) with data from 1950 to 2100 were simulated, with inclusion of theoretical reservoir operation that would occur during or in reaction to the simulated weather – an extension of stochastic reservoir simulation that has been discussed in scientific literature for estimating peak flows in regulated systems (Micovic et al., 2016). After consultation with OBWB, design levels for the recent period (2006 – 2035) were recommended as well as projected design levels (which implicitly consider climate change) for Mid-Century (2041 – 2070) and End of Century (2071 – 2100).

Flood levels on Osoyoos Lake are affected not only by direct inflows to the lake, but also by flows on the Similkameen River which joins the Okanogan River approximately 5 km downstream from the lake outlet. High flows on the Similkameen River impose a backwater control on lake outflows which may result in a significant increase in Osoyoos Lake levels.

A previously established empirical relationship (Summit Environmental Consultants 2010) between Osoyoos Lake levels, the discharge of the Similkameen River at Nighthawk, and outflows from Osoyoos Lake was used in a separate water balance model to account for Similkameen River backwater effects and to simulate Osoyoos Lake levels under backwater conditions for both observed historic conditions and for the climate ensembles.

The final recommended design levels and flows are provided in section 3.5 and a list of recommendations and areas of future work are provided in section 3.6.

3.1.1 Limitations on the Hydrology Component of this Study

The following limitation of the hydrology component should be recognized:

- Potential future regulation changes for Okanagan and Kalamalka/Wood Lake have thus far only been estimated in cooperation with the current operator, Shaun Reimer. For true changes to future regulations, a much larger group of stakeholders will need to be involved. These model results can only illustrate the potential impact of such changes on future levels. Discussions about these potential future operations changes should begin within the next 5 years.
- The quality of any hydrologic model is directly dependent on the quality of the forcing data (temperature and precipitation in this case). Typically, substantial time is spent in developing and testing appropriate driving data based on surface weather observations. However, in this study, NHC was provided with gridded forcing data to use for hydrologic modelling that was produced by another consultant. The nature of gridded data means that it must essentially be used as-is; the multiple steps that the data goes through when it is created means that the data is very difficult to check for quality. Additionally, even if issues are found, they cannot be corrected without rebuilding the dataset entirely.
- There are inherently large amounts of uncertainty in estimation of extreme river flows or lake levels. Extrapolation is required to move from the record of events that have happened (even over the course of 60 or more years) to estimate 200-year ARI or higher lake levels or flows. Thus, it must be understood that these design level and flow estimates have a large amount of uncertainty associated with them.
- Along with the inherent uncertainty in extrapolating to design flow and levels, there is uncertainty in the climate model output used to predict these changes into the future. This limitation was discussed in Chapter 2. This large uncertainty in climate projections, combined with the uncertainty in the reservoir operations response meant that future design levels could only be projected through the 2041-2070 period (referred to as Mid-Century for simplicity) rather than the more common climate change projections to the end of the century. Even these mid-century levels are still highly uncertain.

- A hydrologic model is specific to the purpose and scale that it was designed for. This Raven model was developed for the purposes of peak flow modelling on the scale of the mainstem of the ORB (on the order of 1000s of km^2 watershed area), and subbasin calibration is expected to be valid at watersheds as small as roughly 50-100 km^2. Simplifications were made for processes expected to only be relevant for low flows and smaller scales. Some examples include: the lack of inclusion of water demand, the lack of inclusion of water diversions between basins, and simplified representation of agricultural and forest harvesting landscapes. Thus, the model is not intended to be used for predictions during low flow periods in its current form.
- Lake level and design flow estimates are dependent on human operators in the real Okanagan River Basin (ORB). The operations rules implemented in this model are dependent on the operators following without fault. Thus, infrastructure damage or malfunction, or human error, could cause these design levels and flows to be exceeded or impacted in some way.
- Data limitations can inhibit the model's capability to effectively simulate past or future conditions. In particular, Ellison Lake has limited data availability for calibration, and limited information on the major inflow source to the lake, Swalwell Lake. Major releases from Swalwell Lake could impact Ellison Lake levels.
- Osoyoos Lake levels are affected both by lake inflows and by high flows on the Similkameen River which joins the Okanogan River downstream from Osoyoos Lake and which exerts backwater controls on lake outflows under certain conditions. While high quality records are available of observed historical flows on the Similkameen, there is currently no hydrologic model of the Similkameen River basin comparable to the Raven model of ORB and currently no means of simulating Similkameen River flows for the climate ensembles used in the present study. Similkameen River flows for the climate ensembles for the present study were therefore estimated by regression against simulated flows from Shatford Creek, a west-side tributary of the Okanagan River which shares a common boundary with the Similkameen basin. The regression relationship is relatively weak and resulting estimates of Similkameen River flows correspondingly uncertain. Work is currently in progress to develop a Raven hydrologic model of the Similkameen River basin; hence this limitation is expected to be rectified in the future.
- A previously established multiple regression relationship between Osoyoos Lake levels, the discharge of the Similkameen River at Nighthawk, and outflows from Osoyoos Lake was used to simulate Osoyoos Lake levels under backwater conditions. Application of this relationship in the present study involves extrapolation far beyond the relatively narrow range of historical data from which the relationship was developed, introducing additional uncertainty into estimates of extreme Osoyoos Lake levels.
- The flood of record (2017) was only simulated using preliminary forcing datasets (temperature and precipitation), which provided forcing weather data through 2017. However, there were substantial input data errors identified in this dataset, primarily in high

elevation precipitation. Thus, the simulation results were not considered reliable. The final weather forcing dataset ended in 2012, and thus the erroneous data for the 2017 event was not corrected. This resulted in the inability to calibrate the hydrologic model to 2017.

- This study did not include an assessment of the consequences of dams overtopping, malfunctioning, or infrastructure damage. The results presented here were produced under the assumption of all equipment working properly.

3.2 Flood Event of Record (2017)

The nature of the spring freshet in recent years indicates that the hydrology of the ORB is changing; the ORB experienced flooding in both 2017 and 2018, with lake levels on Okanagan and Kalamalka reaching new record levels in 2017. Flooding on Okanagan Lake, Kalamalka Lake and Wood Lake are dependent on the water that flows into the reservoir, from either tributary streams or via non-point sources, referred to as reservoir inflows. Reservoir inflows (Q_{in}) cannot be measured directly, only coarsely estimated through a water balance calculation as:

$$Q_{in} = \Delta S - Q_{out} + P_{direct} - E_{direct} + GW_{in} - GW_{out}$$

where ΔS is the change in storage, Q_{out} are the reservoir releases, P_{direct} and E_{direct} are direct precipitation onto and evaporation from the reservoir surface, and GW_{in} and GW_{out} are groundwater gains and losses to the reservoir.

Aside from Q_{out}, most terms of the reservoir water balance cannot be directly measured. In particular, the groundwater flux is largely unknown and must be assumed to be a net 0. ΔS can be coarsely estimated using the reservoir area and the change in daily reservoir levels (Ashlee Jollymore, BC River Forecast Centre, pers. communication 2019). Often direct precipitation and evaporation are also assumed to be have a net zero effect or lumped together with Q_{in}; this grouping is sometimes referred to as net reservoir inflow. However, for reservoir inflow calculations, direct precipitation and evaporation were obtained from the hydrologic model in order to reduce noise in inflow calculations and allow a more direct comparison with modelled reservoir inflow from the Raven hydrology model. Note that the effect of human consumption is implicit within the ΔS calculation in this equation and is likely one reason that calculated reservoir inflows can become negative during summer months.

Calculated reservoir inflows for Okanagan Lake are shown in Figure 3-1 for the four largest events on record: 1948, 1972, 1997, and 2017. This figure illustrates that inflows in the year 2017 followed a substantially different pattern than previous high flow years. The inflows in 2017 peaked much earlier and ramped up much faster than any previous year. Even in a completely natural system, this departure from previous high flow years would be likely to cause extreme water levels. This was compounded further in the Okanagan system, which is heavily managed and follows a rule system dependent on peak flows occurring at roughly the same time every year.

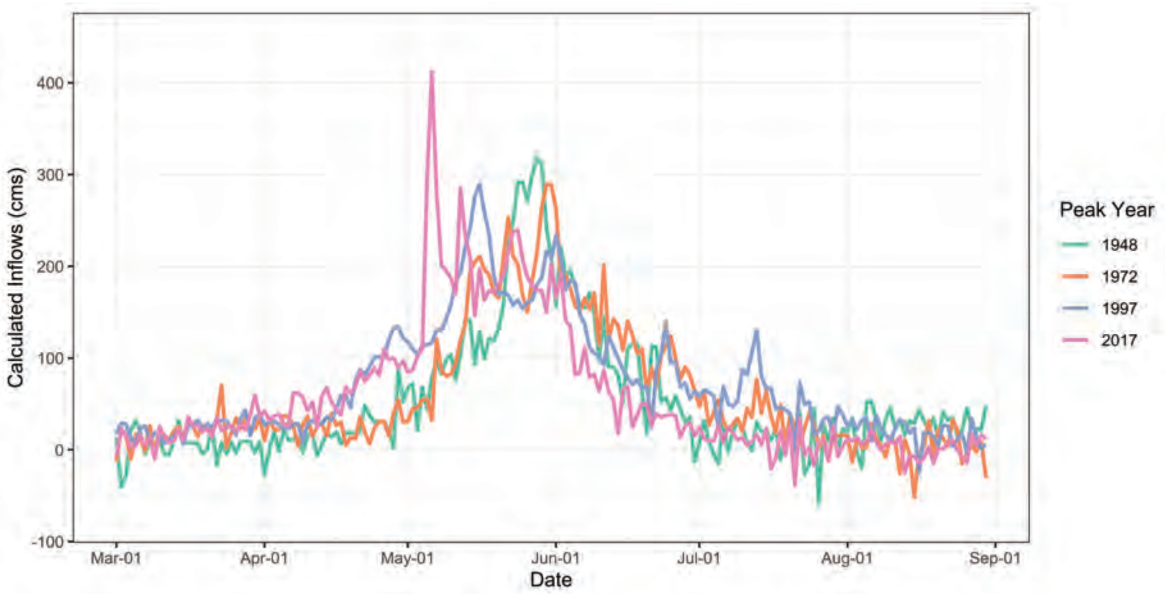


Figure 3-1 Calculated inflows to Okanagan Lake for select peak years.

Table 3-1 summarizes the volume, maximum daily inflow, and time to peak for each event. The highest maximum daily inflow occurred in 2017 with a maximum daily inflow almost 100 m^3/s greater than the second largest event in 1948. The 1997 event had the largest total volume and had a time to peak about 10 days shorter than 1948 or 1972 events. The 2017 event had a similar total volume however, the time to peak was significantly shorter than all three of the other events. This large volume over a shorter time period was likely the primary factor that contributed to the historic flooding observed in 2017. However, caution should be exercised when interpreting calculated inflows, as they are back calculated via the reservoir mass balance and hence data can be quite noisy. For example, note the low flow periods in Figure 3-1, which are quite noisy and include negative values.

Table 3-1 The four largest calculated inflow events to Okanagan Lake (1945 – 2017).

Year	Max Daily inflow (m^3/s)	Peak Date	Time to Peak (days)	Total Volume (m^3)[1]
1948	318	1948-05-28	43	635,000,000
1972	290	1972-05-30	45	657,000,000
1997	289	1997-05-16	31	771,000,000
2017	412	2017-05-06	21	752,000,000

1. Total volume calculated from April 15 to June 15.

3.3 Simulating the Hydrology of the Okanagan Basin and OLRS Operations

3.3.1 Approach

To simulate the hydrology of the ORB a hydrologic model was developed using the Raven hydrologic model framework (Raven) (Craig et al., 2020; Craig and the Raven Development Team, 2019). The model captures the natural hydrology of the basin as well as the different operations of the OLRS. The general approach to development was as follows:

- All necessary data for the hydrologic model was compiled and processed
- The model structure was configured and manually calibrated
- Once the model structure was set, automatic calibration using the Ostrich Calibration Tool (Ostrich) (Matott, 2017) was completed for the natural (unregulated) portions of the ORB, including unregulated subbasins within the ORB and calculated reservoir inflows to Okanagan and Kalamalka/Wood Lake.
- OLRS operations were then incorporated into the model and the regulated portions of the model were calibrated

More details about Raven and the model development process are discussed in section 3.3.3**.**

Once the model was calibrated, it was validated using a validation approach which focused on internal performance of non-calibration basins (section 3.3.3). An ensemble climate set of 50 different climate realizations from 1950-2100 was then run through the model. The results were then used to determine statistic probabilities of flood levels throughout the ORB (section 3.4).

OLRS Operations

Mainstem reservoir lakes were defined by the client in the RFP. These are Ellison Lake, Wood Lake, Kalamalka Lake, Okanagan Lake, Skaha Lake, Vaseux Lake, and Osoyoos Lake. In addition to the mainstem lakes, Swan Lake, Swalwell (Beaver) Lake, Oyama Lake, Ideal Lake, and Otter Lake were explicitly modelled as reservoirs as they were expected to have significant impacts on their respective basins. Table 3-2 summarizes the characteristics of the lakes from a variety of reports.

Table 3-2 Summary of modelled lake reservoir information.

Lake	Surface Area (million m^2)	Volume (million m^3)	Mean Depth (m)[1]	Hydrologic Model crest height (m)
Ellison	2.05	5.36	2.5	425.392
Wood	9.30	200	22	n/a
Kalamalka	25.9	1,520	59	391.42
Okanagan	348	26,200	76	339.875
Skaha	20.1	558	26	336.044
Vaseux	2.75	17.7	6.5	327.477
Osoyoos	15.0	254	15	278.063
Swalwell (Beaver)	2.53	16.4	9	1,342.605
Swan	4.10	17.5	4.3	389.804
Oyama	3.64	24.4	7	1357.26
Ideal (Belgo)	1.46	6.74	**13**	1,298.432
Otter	0.941	1.72	**6**	347.808

1. Depths in **bold** are maximum depths, mean depths not reported.

Note that in the hydrologic model, Kalamalka and Wood lakes were modelled as one unit as recommended by the RFP. This was verified by plotting recorded Kalamalka Lake levels against recorded Wood Lake levels. For lake levels on Kalamalka, WSC 08NM143 was used for between 1967-08-09 and 1971-12-13. From 1971-12-14 to 1973-03-02 WSC gauge 08NM183 was used. Figure 3-2 shows a plot of days where there was data on both lakes. There is a strong correlation between the two with an R^2 of 0.975. Therefore, the assumption that the two lakes act as one hydrologic system appears to be valid.

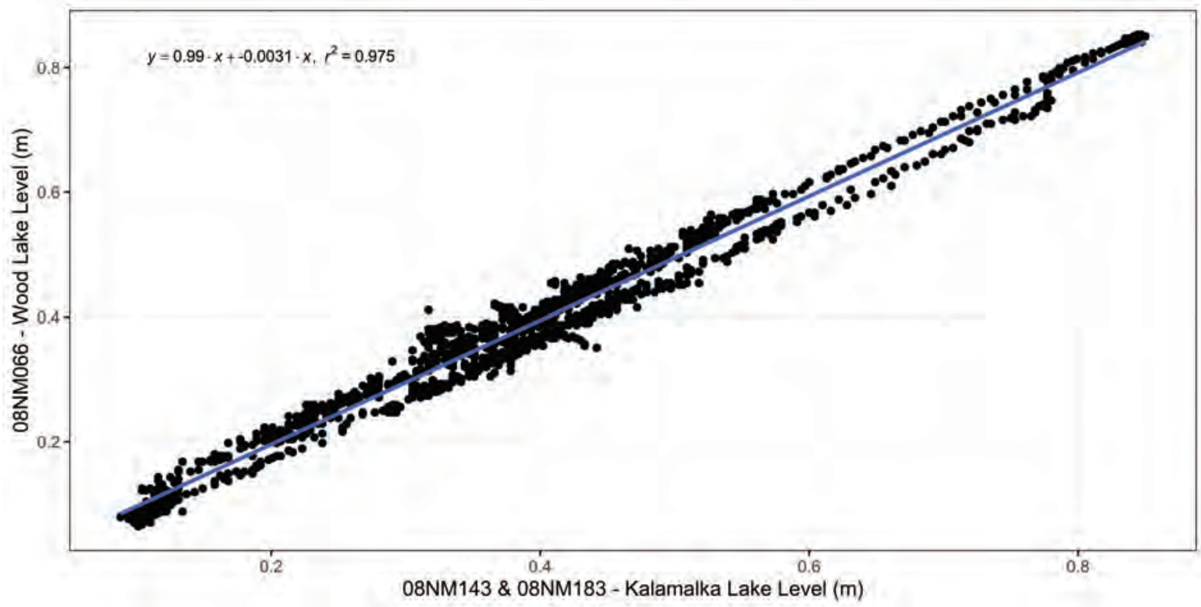


Figure 3-2 Comparison of Kalamalka and Wood Lake Levels.

Lake operations have changed over time due to changing regulations and priorities, additionally there is some subjectivity due to the nature of human operations. NHC worked closely with the lead FLNRORD reservoir operator, Shaun Reimer, to simplify reservoir operations in the Raven model. This required assuming constant operating rules for the entire simulation period, even though operations have changed over time. Emulating present day operation rules was deemed the appropriate modelling course; it is assumed that future operations will follow these rules until they are updated. A summary of the operations data is provided in section 3.3.3.

3.3.2 Data Compilation

This section describes the data sources required to build the ORB hydrology and operations model. Spatial and bathymetric data was required to discretize model response units and inform parameterization. Climate data was required to drive model simulations and flow and lake level data was required for model calibration and validation. Information about OLRS operations was also required for simulation of the regulated portions of the model. The following sections summarise what data was collected, how it was processed, and how it was used during model simulation and development.

Spatial and Bathymetric Data

Table 3-3 summarizes the spatial data that was used for model development. For soils data on the US side of the basin the closest Canadian soil polygon was extended south.

Table 3-3 Spatial information used during model development.

Data Type	Description	Coverage	Source
Digital Elevation Map (DEM)	3' resolution data	Entire ORB	USGS[1]
Lidar	1 m resolution		Provided by OBWB[2]
Hydrography	1:20,000 hydrography; delineated lakes, watercourses, and drainage basins	BC portion of ORB	BC Fresh Water Atlas
Landcover	300 m gridded landcover (Grass/Shrubs, Forest, Mixed Forest, Urban, Lake)	Entire ORB	ESA GlobCover 2009
Landcover	30 m landcover data (Urban, Lake)	BC portion of ORB	Government of Canada
Soil	STE_SOIL_SURVEYS layer from Soil Survey Spatial	BC Portion of ORB	BC Ministry of Environment and Climate Change Strategy

1. Source: https://catalog.data.gov/dataset/usgs-national-elevation-dataset-ned, accessed 31 March 2020.
2. Discussed in further detail in section 5.2.

Bathymetric data was necessary for model development. A detailed discussion on data used is provided in section 5.2.

Climate Data

Hydrologic model forcing variables (daily maximum and minimum temperature and daily total precipitation) were obtained in gridded format from the Okanagan-Similkameen gridded meteorological dataset in a 500 m x 500 m grid for the years 1945-2012[1] (section 2.5.1). This gridded dataset was created via a combination of the daily temporal resolution PNWNAMet dataset (based on surface weather observations) produced by the Pacific Climate Impacts Consortium (PCIC)[2] and 500m spatial resolution monthly climatology surfaces via the methods of Sobie and Murdock (2017). NHC aggregated the dataset to an irregular grid aligning 1:1 to each model hydrologic response unit (HRU). The HRU is the smallest spatial discretization represented within the Raven model, described in section 3.3.3. Total precipitation data was partitioned into rain and snow using the precipitation partitioning equation from the HBV hydrologic model (Bergstrom, 1995).

[1] Gridded meteorological forcing dataset produced by Associated Environmental for the OBWB (2019).

[2] https://www.pacificclimate.org/data/daily-gridded-meteorological-datasets, accessed 31 March 2020.

Snow pillow data was collected from the BC Ministry of Environment (MOE) for calibration purposes and for replicating the forecast described in subsequent sections. The stations are summarized in Table 3-4.

Table 3-4 Acquired snow data.

Station No.	Station Name	Data Type[1]	Period of Record
2F05	Mission Creek	Manual	1939 – 2005
2F05P	Mission Creek	Automatic	2003 – 2020
2F08	Greyback Reservoir	Manual	1953 – 2020
2F08P	Greyback Reservoir	Automatic	2016 – 2020
2F10	Silver Star Mountain	Manual	1959 – 2020
2F10P	Silver Star Mountain	Automatic	2015 – 2020
2F11	Isintok Lake	Manual	1965 – 2020
2F12	Mount Kobau	Manual	1966 – 2020
2F18	Brenda Mine	Manual	1969 – 2014
2F18P	Brenda Mine	Automatic	2003 – 2020
2F19	Oyama Lake	Manual	1969 – 2020

1. Automatic data reported as SWE (mm) from automated snow pillows, manual data reported as snow depth (cm) from snow courses.

Flow Data

Table 3-5 summarizes the discharge observations that were considered during hydrologic model calibration and validation. Note that stations without data after 1990 were only used during the manual calibration period. Basin types consist of study lakes which are the main lakes identified in the RFP, upland lakes which correspond to upland lakes introduced in Table 3-2, Environmental Flow Needs (EFN) basins which correspond to the 19 basins modelled by Associated Environmental (2020), or Other (unclassified).

Table 3-5 Hydrometric stations used for model development and calibration.

Gauge No[1,2]	Gauge Name	Basin Type	Period of Record	Gauge Status	Data Type[3]	Drainage Area (km^2)[4]	Reg? (Y/N)[4]
08NM118	Penticton Creek at the mouth	EFN	1950-1972	Discontinued	Q	177	Yes
08NM150	Shingle Creek at the mouth	EFN	1969 - 1981	Discontinued	Q	308	Yes
08NM155	Trepanier Creek at the mouth	EFN	1969 - 1981	Discontinued	Q	254	Yes
08NM157	Powers Creek at the mouth	EFN	1969 - 1982	Discontinued	Q	144	Yes

Gauge No[1,2]	Gauge Name	Basin Type	Period of Record	Gauge Status	Data Type[3]	Drainage Area (km^2)[4]	Reg? (Y/N)[4]
08NM158	Trout Creek at the mouth	EFN	1969 - 1982	Discontinued	Q	764	Yes
08NM161	Equesis creek near the mouth	EFN	1969 - 1982	Discontinued	Q	199	Yes
08NM174*	Whiteman Creek above Bouleau Creek	EFN	1970-2019	Active	Q	114	No
08NM200	Inkaneep Creek near the mouth	EFN	1973 - 2019	Active	Q	227	Yes
08NM246	Vaseux Creek near the mouth	EFN	2006-2010	Discontinued	Q	296	No
08NM020	B.X. Creek above Vernon intake	Other	1921-1999	Active	Q	55.7	Yes
08NM037	Shatford Creek near Penticton	Other	1919-2019	Active	Q	101	Yes
08NM116	Mission Creek near East Kelowna	Other	1949-2019	Active	Q	795	Yes
08NM134	Camp Creek at mouth near Thirsk	Other	1965-2019	Active	Q	34.6	No
08NM142*	Coldstream Creek above municipal intake	Other	1967-2019	Active	Q	60.6	No
08NM146	Clark Creek near Winfield	Other	1968-2019 (discontinuous)	Active	Q	15.3	No
08NM153	Deep Creek at the mouth	Other	1969 - 1975	Discontinued	Q	306	Yes
08NM159	Peachland Creek at the mouth	Other	1969 - 1982	Discontinued	Q	150	Yes
08NM160	Vernon Creek near the mouth	Other	1969-1999	Discontinued	Q	751	Yes
08NM171*	Vaseux Creek above Solco Creek	Other	1970-2019	Discontinued	Q	117	No
08NM173	Greata Creek near the mouth	Other	1970-2019	Active	Q	40.7	No
08NM232	Belgo Creek below Hilda Creek	Other	1976-2019	Active	Q	70.7	Yes

Gauge No[1,2]	Gauge Name	Basin Type	Period of Record	Gauge Status	Data Type[3]	Drainage Area (km^2)[4]	Reg? (Y/N)[4]
08NM233	Mission Creek above Pearson Creek	Other	1977 - 1982	Discontinued	Q	233	Yes
08NM002	Okanagan River at Okanagan Falls	Study Lake	1915 - 2018	Active	Q	6720	Yes
08NM050	Okanagan River at Penticton	Study Lake	1920 - 2018	Active	Q	5980	Yes
08NM065	Vernon Creek at outlet of Kalamalka Lake	Study Lake	1927 - 2018	Active	Q	569	Yes
08NM066	Wood Lake at inlet to Oyama Canal	Study Lake	1928 - 1973	Discontinued	WL		Yes
08NM067	Ellison Lake near Winfield	Study Lake	1968 - 1980	Discontinued	WL		Yes
08NM071	Okanagan Lake at Penticton	Study Lake	1920 - 1974	Discontinued	WL		Yes
08NM073 /12439000	Osoyoos Lake near Oroville, WA	Study Lake	1965 - 2019	Active	WL		Yes
08NM083	Okanagan Lake at Kelowna	Study Lake	1943 - 2018	Active	WL		Yes
08NM084	Skaha Lake at Okanagan Falls	Study Lake	1943 - 2018	Active	WL		Yes
08NM127 /12439500	Okanagan River at Oroille, WA	Study Lake	1942 - 2019	Active	Q	8210	Yes
08NM143	Kalamalka Lake at Vernon Pumphouse	Study Lake	1967 - 2018	Active	WL		Yes
08NM162	Vernon Creek at inlet to Ellison Lake	Study Lake	1970 - 1974	Discontinued	Q	127	Yes
08NM182	Vernon Creek at outlet of Ellison Lake	Study Lake	1971 - 1974	Discontinued	Q	138	Yes
08NM183	Kalamalka Lake at outlet of Oyama Canal	Study Lake	1971 - 1979	Discontinued	WL		Yes
08NM243	Vaseux Lake near the outlet	Study Lake	1991 - 2018	Active	WL		Yes

Gauge No[1,2]	Gauge Name	Basin Type	Period of Record	Gauge Status	Data Type[3]	Drainage Area (km^2)[4]	Reg? (Y/N)[4]
08NM247	Okanagan River below McIntyre Dam	Study Lake	2012 - 2016	Active	Q	7150	Yes
08NM022	Vernon Creek at oultet of Swalwell Lake	Upland Lake	1921 - 1996	Discontinued	Q	62.4	Yes
08NM062	Swalwell Lake near Okanagan Centre	Upland Lake	1926 - 1992	Discontinued	WL		Yes
08NM123	B.X. Creek below Swan Lake control dam	Upland Lake	1959 - 1978	Discontinued	Q	120	Yes
08NM125	B.X. Creek above Swan Lake control dam	Upland Lake	1959 - 1979	Discontinued	WL		Yes
08NM231	Ideal Lake near the outlet	Upland Lake	1963 - 1980	Discontinued	WL		Yes

1. Gauges marked in bold with (*) were used for regional calibration of the unregulated portions of the Raven hydrologic model.
2. Second numbers represent USGS gauge number.
3. Primary data type, either Discharge (Q) or Stage (WL).
4. As reported by WSC, regulation can refer to dam operations or significant withdrawals.

Operations Data

Reservoir operations were determined based on published rules of the OLRS, found in AE (2017), and refined via personal communication with FLNRORD Okanagan system chief operator, Shaun Reimer. The OLRS reservoir operations plan contains information for operators both in low flow and high flow (freshet) situations. As this model was concerned with high flows and their effects on flood inundation, only operations data used directly in model simulations is included in this section. For reservoir operations, the summer low-flow period was used simply as a time to ensure that reservoir levels reached their target pre-freshet levels. Modelled flows during the summer are likely to be higher than observations. Water that would have been removed via withdrawal (in reality) was instead removed from the reservoirs via releases (in the Raven model). While this simplifying assumption may lead to long term baseflow simulation issues in a standard model; it is expected that this is largely compensated for via the stage-based reservoir management targets of the mainstem reservoirs

Monthly target reservoir levels at Okanagan and Kalamalka/Wood Lake are dependant on lake inflow forecasting completed by the BC River Forecast Center (RFC). The RFC forecasts reservoir inflows for Okanagan Lake and Kalamalka Lake using a series of equations developed via principal components regression (Dave Campbell, BC RFC Head, personal communication, 2019). The equations are fitted by month and use predictors from the monthly manual and continuous automated snow survey sites within the basin, along with observations of antecedent reservoir inflows and antecedent precipitation onto the basin. The predictand of each monthly equation (from February – May) is a total summer inflow volume forecast for the reservoir. Using model state variables, rather than snow, precipitation, and inflow observations, NHC emulated the RFC monthly forecast equations to continuously update lake target levels within the operations model. This internal emulation of the forecasts provided the ability to produce virtual forecasts for the present and future ensemble weather predictions. In other words, realistic forecasts could still be made for virtual weather situations.

Table 3-6 summarizes the lake targets for Okanagan and Kalamalka. AE (2017) also specifies minimum discharge requirements for environmental flow needs. For Kalamalka Lake the minimum outlet discharge is constant at 0.085 m^3/s while for Okanagan it is a function of fish spawning times.

Table 3-6 Target Lake elevations for Okanagan and Kalamalka Lakes.

Month	Okanagan Lake		Kalamalka Lake	
	Volume Forecast (million m^3)	Target Lake Elevation (m)[1]	Volume Forecast (million m^3)	Target Lake Elevation (m)[2]
January	-	341.96	-	391.45
February	< 430	342.26	< 15	391.65
	>430	341.76	> 15	391.45
March	< 620	342.26	< 15	391.65
	> 620	341.71	> 15	391.45
April	< 250	342.70	< 30	391.75
	370 – 500	341.66	> 30	391.65
	> 500	341.56		
May	-	342.70	-	391.85
June	-	342.66	-	391.95
July	-	342.46	-	391.82
August	-	342.26	-	391.75
September	-	342.11	-	391.65
October	-	342.06	-	391.60
November	-	342.06	-	391.55
December	-	342.06	-	391.50

1. Adjusted from original values based on WSC datum (340.236 m) by datum correction of 0.215 m.
2. Converted to CGVD2013 datum by adding 0.252 m.
3. There was a typo in the original document (it reported 324 m) which has been corrected in this table.

Osoyoos lake has monthly reservoir targets and minimum levels. For reservoir targets, Osoyoos does have a special drought condition scenario that is a function of flows on the Similkameen. This forecast was not included in the current model project, but this is an area for future work, should the Raven model developed here be extended for application during low flow conditions. Table 3-7 summarizes the model reservoir target levels for these constant targets. Note that due to backwater effects of the Similkameen River on Okanogan River downstream of Osoyoos Lake outlet (section 3.3.4) the reservoir target levels are not relevant during high Similkameen River flow situations.

Table 3-7 Osoyoos Lake operations.

Month	Target Lake Elevation (m)	Minimum Allowable Stage (m)
January	277.92	277.22
February	277.92	277.22
March	277.92	277.22
April	278.02	277.52
May	278.1	277.52
June	278.1	277.62
July	278.1	277.82
August	278.1	277.82
September	278.1	277.82
October	278.02	277.62
November	277.92	277.52
December	277.92	277.22

1. (IJC, 2013); Converted to CGVD2013 datum by adding 0.12 m.

Swan Lake is operated by stoplogs at the outlet (Ecora, 2019b). The (Ecora, 2019b) report provided discharge rating curves for 0-, 1-, 2-, 3-, 5-, and 5-stoplog scenarios. We included a simplified annual stoplog cycle in the model for realistic Swan Lake operations based on interpretation of this report.

3.3.3 Hydrologic Operations Model

NHC created a hydrologic model of the entire ORB using the Raven hydrologic modelling framework (Craig et al., 2020; Craig and the Raven Development Team, 2019). The model incorporated natural portions of the basin including snowmelt and in-channel hydrologic routing as well as explicit reservoir representation. The model did not consider irrigation demands or withdrawals as the focus of the model was on capturing hydrologic behaviour during flood conditions.

Raven Hydrological Modelling Framework

Raven is an open-source hydrologic model platform that is under active development, with a focus on mathematically stable and computationally efficient integration of a wide variety of hydrologic model routines. Raven is currently being used by multiple organizations within Canada for reservoir management and flood forecasting, including BC Hydro, TransAlta, and New Brunswick ELG.

Raven contains a large library of hydrological process algorithms and forcing function generators. This provides Raven with significant flexibility in simulation of hydrological processes, including snow accumulation and melt, at a user-determined level of detail and complexity. The recommended approach when developing a Raven model is to begin with a simple model template and only add complexity as necessary for the project goals; this was the general approach followed for this model.

After producing satisfactory simulations of the true historical period, the model was run in ensemble, that is it was run through all 50 climate scenarios from 1950 – 2100 during the course of model execution. During ensemble model execution the Raven hydrologic model runs twice, the first time generating the forcing data that is used for the forecast (precipitation and SWE) and the evaporation on the lakes. The model then generates the RFC forecast for each ensemble and relevant reservoir targets and executes the Raven hydrologic model a second time with these inputs to produce the final results.

Model Development

The first, and typically most time consuming, step to model development is determining the spatial organization. Raven supports a generic spatial discretization approach whereby the ORB is subdivided into subbasins, which are collections of hydrological response units (HRUs) consisting of relatively homogeneous land parcels with a unique hydrological signature. Water is distributed vertically within HRUs and redistributed laterally via routing (representing transport in stream channels). The user can define any spatial setup that is desired; the geometry of the HRU may conform to a fixed grid (as with many fully-distributed models), to an irregular portion of a subbasin (a semi-distributed approach) or the entire model may consist of a single HRU/subbasin (a lumped model). Figure 3-3 shows an example schematic of the conceptual spatial model used by Raven.

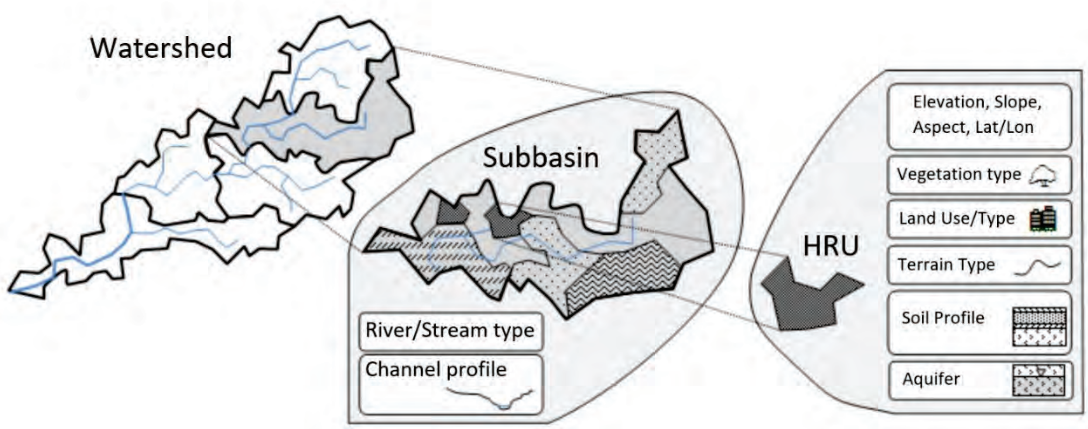


Figure 3-3 Basin discretization in the generalized Raven spatial configuration (Craig and the Raven Development Team, 2019).

The ORB was divided into 64 subbasins based on a combination of the practical needs of the model (i.e. where flows were needed for analysis and where observation data was available for calibration) and a hydrologic understanding of the model area. The subbasins were then broken down into non-contiguous HRUs. These were defined by a combination of elevation bands, landcover types, and soil textures summarized in Table 3-3. Major subbasins are shown in Figure 3-4 while a summary of HRU delineation is provided in Figure 3-5.

HRUs were then populated with the required attributes:

- Centroid latitude and longitude
- Mean elevation
- Mean aspect
- Mean slope
- Dominant (modal) landcover from the ESA GlobCover 2009 300-m gridded landcover classification (Arino et al., 2009)
- Dominant soil texture and drainage class from the STE_SOIL_SURVEYS data source from GeoBC[1]
- Urban and surface water from the 30 m ACI raster dataset

The CleanHRUs() function in the 'RavenR' package[2] for the statistical software R (Hornik, 2016) was used to aggregate sliver HRUs into larger pieces. This resulted in a total of 1337 HRUs. Raven requires that each HRU is a member of a vegetation class, land use class, and soil class. In many cases (including this one) the vegetation and land use classes are the same. Information from the GlobCover and ACI datasets was used to create five simplified land use and vegetation categories (which dictate interception properties, snowmelt, evapotranspiration, etc.). These categories were defined as in Table 3-8. In addition to this, the higher resolution ACI values overrode the Urban and Lake categories.

[1] https://catalogue.data.gov.bc.ca/dataset/20150a67-5a2d-425f-8216-ff0f97f68df9, accessed 31 March 2020.

[2] https://github.com/rchlumsk/RavenR, accessed 31 March 2020.

Table 3-8 Landcover categories in the GlobCover data.

GlobCover Category	Raven Land use & Vegetation Class
Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)	GrassShrubs
Closed (>40%) needleleaved evergreen forest (>5m)	Forest
Open (15-40%) needleleaved deciduous or evergreen forest (>5m)	MixForest
Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)	MixForest
Mosaic forest or shrubland (50-70%) / grassland (20-50%)	MixForest
Mosaic grassland (50-70%) / forest or shrubland (20-50%)	GrassShrubs
Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)	GrassShrubs
Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	GrassShrubs
Sparse (<15%) vegetation	GrassShrubs
Artificial surfaces and associated areas (Urban areas >50%)	Urban
Water bodies	Lake

A similar procedure was performed with dominant soil texture to simplify the basin into two soil categories (Table 3-9)**.** Though there are nine identified categories, the texture is dominated by silt and loam in the northern portion of the ORB, and Sandy Loam for the rest; thus it was determined that two categories would be an appropriate complexity level for a model of this scale. The HBV soil model includes three horizons: the active layer, which controls soil evaporation and infiltration, the fast reservoir layer, which controls storm runoff, and the slow reservoir layer, which controls baseflow. Investigation of measured soil depths at soil pit sites within the ORB (Knox Mountain, Oyama, Penticton sites) informed the soil horizon depths and parameter ranges used during model calibration to assure that realistic soil parameters were used (Wittneben, 1986).

Table 3-9 Soil textures from BC Government soil maps used for the model soil profile scheme (Wittneben, 1986).

Soil texture	Raven Soil Profile
- (Unknown)	Coarse
C (Clay)	Medium
HC (Heavy Clay)	Medium
L (Loam)	Medium
LS (Loamy Sand)	Coarse
SIC (Silty Clay)	Medium
SICL (Silty Clay Loam)	Medium
SIL (Silt loam)	Medium
SL (Sandy Loam)	Coarse

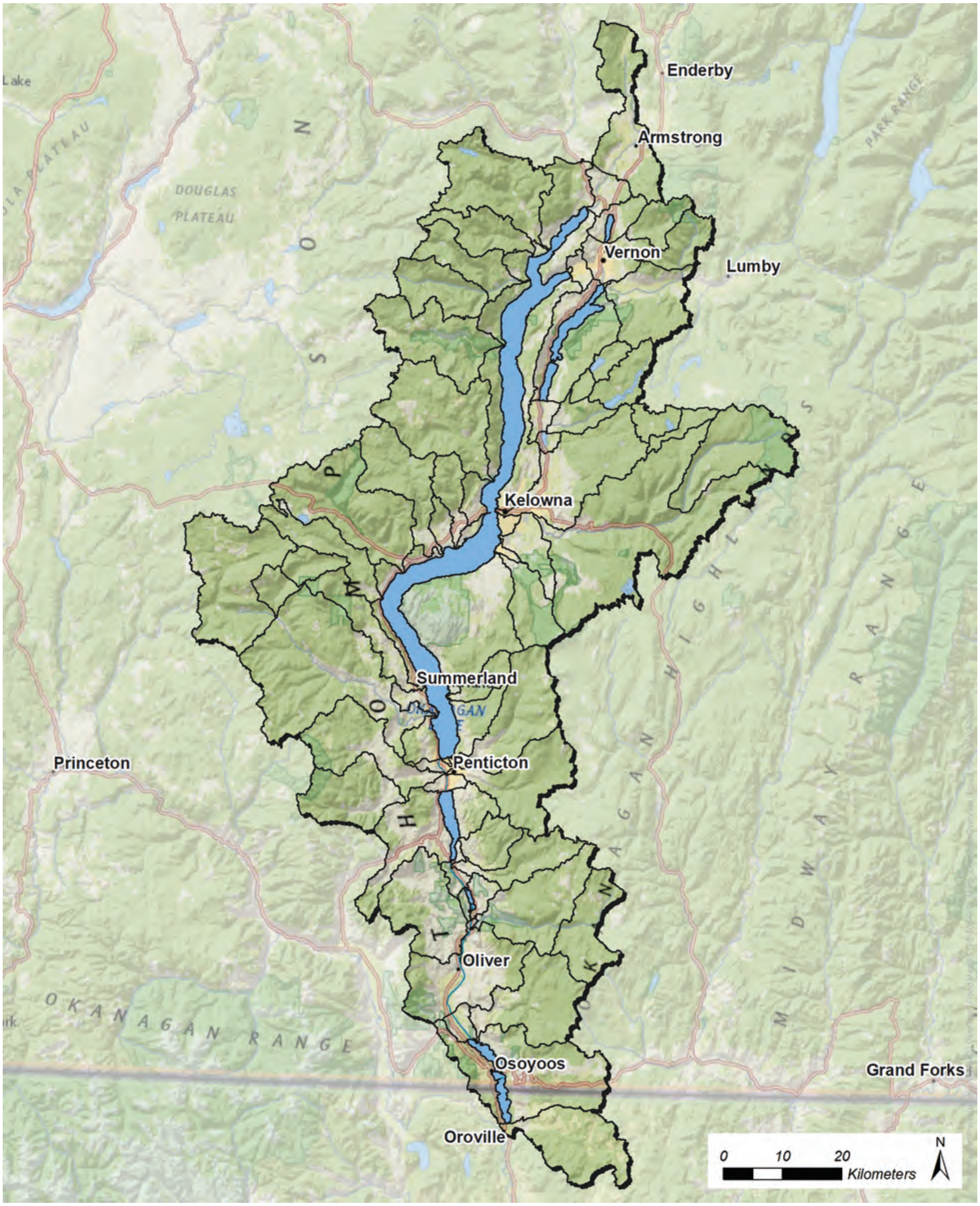
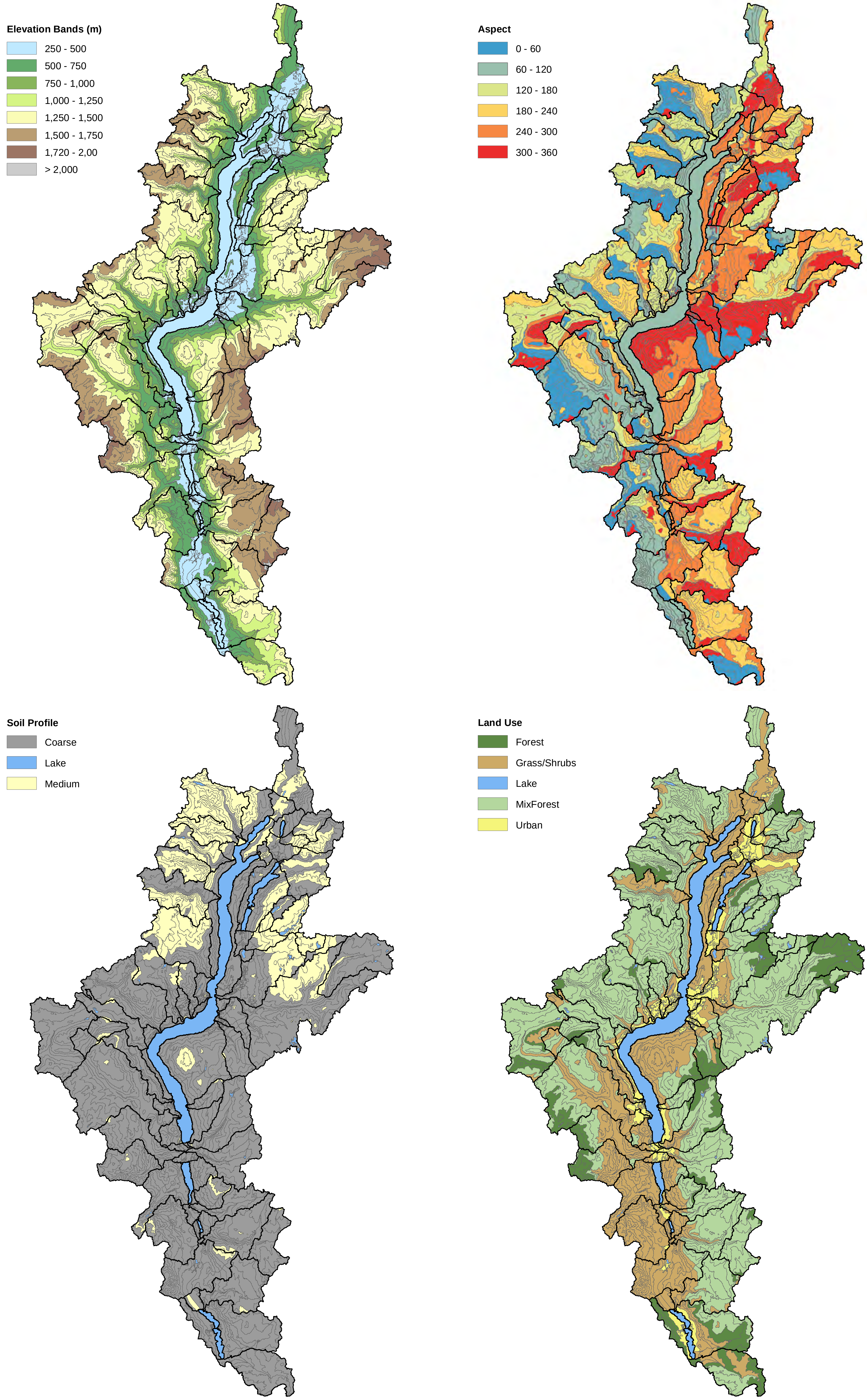


Figure 3-4 Major subbasins of the ORB. Basemap via ESRI.



nhc
northwest hydraulic consultants

Scale - 1:1,000,000

0 10 20 30 Km

N

Coordinate System: NAD 1983 UTM ZONE 11N
Units: METERS

Job: 3004430 | DATE:19-MAR-2019

OKANAGAN HYDROLOGIC MODEL

HRUs

U:\Active\3004430 Okanagan Flood Map\95 GIS\3004430_MAO_Faceted_Figure.mxd

The ORB model structure started with a base HBV-EC (Hamilton et al., 2002) configuration and hydrologic routines were changed as necessary through manual calibration. Initial model parameterization was completed by extracting necessary data from the collected spatial data. Phase 1 of model development focused on natural basin representation and Phase 2 of model development focused on reservoir representation. A model schematic is shown in Figure 3-6.

In a hydrologic model, routing is the movement of water through the model, from headwaters to the model outlet. Three types of routing were implemented in the ORB model: in-catchment routing (between HRUs), channel routing (between subbasins), and reservoir routing. In-catchment routing transforms the direct runoff from each HRU to subbasin outflow using a triangular unit hydrograph method. Channel routing moves water along the major channels between subbasins using a plug flow model. Channel profiles can be provided for the channel routing routine. There were two channel profiles specified for the ORB model, one for the Okanagan River, and one for the other channels. A single representative cross-section of the Okanagan River was developed from surveyed cross-sections of the Okanagan River (WaterSmith Research Inc & Streamworks Consulting Inc, 2014). All other channels were represented with a single cross-section from a survey of Vernon Creek at the outlet of Swalwell Lake (MOELP and MSRM, 1978).

Lake evaporation is a significant portion of the water balance in the ORB, but due to the substantial amount of heat energy stored in large lakes such as the Okanagan, the available routines in Raven do not adequately capture the open water evaporation in the ORB model. To account for this, an override (external model procedure) was created using the empirical equations relating air temperature to lake evaporation in the Okanagan found in Schertzer and Taylor (2009). Along with these equations, if air temperature was below $0^{o}C$, open water evaporation was also set to 0; a simplified assumption of a frozen lake, suitable for this high flow model.

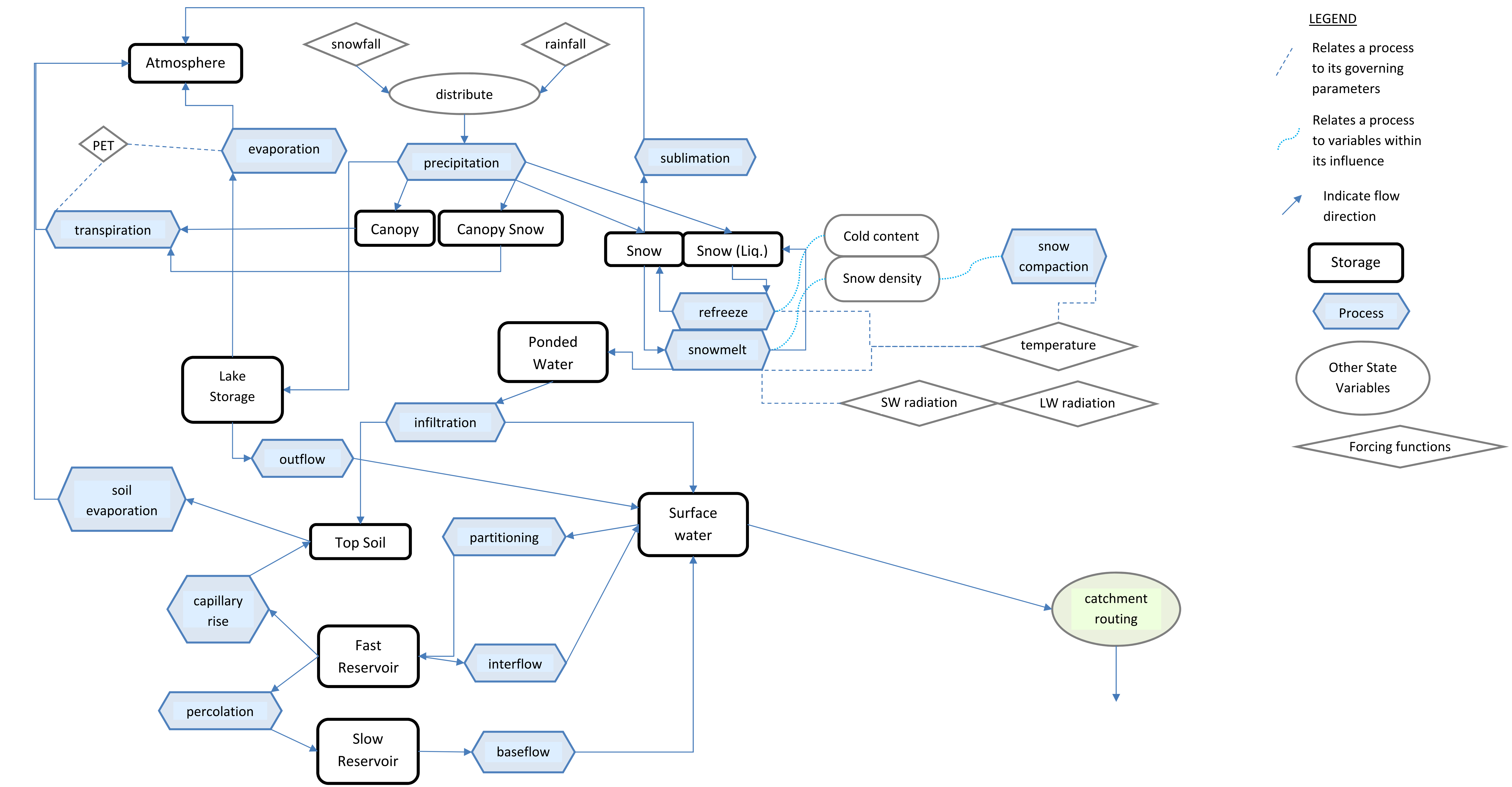


Figure 3 Raven Model Schematic

Model Calibration

The Raven model was first manually adjusted while the final model structure was being determined and to get model parameters into a reasonable range for automatic calibration. This ability to manipulate model processes (rather than only model parameters) is one of the main advantages of the Raven platform, the most appropriate processes can be determined and used through iteration. The manual adjustment process focuses on broad questions such as:

- The general annual hydrograph cycle
- The basin-wide water balance (investigated via regime curves)
- The soil moisture
- Reasonable modelling of snow accumulation and melt when compared with observations.

After the initial setup, automated calibration was carried out on the 30-year period from 1980-2010. This period was chosen because of the reasonably complete coverage of hydrometric observations in the gauged basins.

Due to the substantial flow regulation within the ORB, calibration procedures were only appropriate for natural subbasins within the system. The final calibration parameters on natural basins were then transferred to the rest of the non-calibration basins, referred to as regional calibration. The three calibration subbasins, Coldstream Creek above municipal intake, Vaseux Creek above Solco Creek, and Whiteman Creek above Bouleau Creek, are natural (unregulated) subbasins with basin areas greater than 50 km^2 and data available. Along with these three natural subbasins, the calculated reservoir inflows (described in section 3.2) to Okanagan Lake and Kalamalka/Wood lake were included as calibration targets. Including both natural subbasins and calculated inflows was meant to encompass multiple scales of model calibration. Calibration to reservoir inflows can maximize large scale performance (which is likely the most important for determining flood levels on the major lakes), while calibration to the individual natural subbasins ensures that results still scale down reasonably well to individual creeks. The parameters found during calibration were then transferred to regulated basins to represent the natural processes in those basins.

Automated calibration was performed using the Ostrich model-independent calibration tool (Matott, 2017). Ostrich was used to maximize the mean Nash-Sutcliffe model efficiency (Nash and Sutcliffe, 1970) for the calibration basins in the ORB model. The Nash-Sutcliffe efficiency (NSE) is typically the most commonly used hydrologic model performance statistic since it integrates both the effects of total hydrograph volume and peak flow reproduction accuracy. Values can range from -infinity (bad) to 1 (perfect). An NSE value above 0 indicates that the model has a predictive skill that is better than the mean of all observations. Along with the NSE, we included a percent bias penalty for each of the five calibration targets to ensure the total bias stayed within a reasonable range. Table 3-10 describes the parameters that were manipulated by Ostrich during the calibration procedure.

Table 3-10 Parameters manipulated during the automated calibration procedure.

Parameter group (number of total parameters)	Impact on simulation
Snowmelt degree day factor (three categories), aspect melt correction, minimum melt rate, refreeze factor (6)	Controls the topography and landcover specific snowmelt characteristics
Throughfall fractions and total canopy storage for forested and mixed forest areas separated by rainfall and snowfall (8)	Controls the fraction of precipitation that reaches the ground on areas with a forest canopy
Soil porosity, field capacity, saturation-wilt index and HBV-beta parameter for coarse and medium soil regions (8)	Controls infiltration and soil evaporation from the soil surface
PET correction factors for coarse and medium soil regions (2)	Controls evapotranspiration losses based on empirical regional factors
Percolation and capillary rise rates (6)	Controls movement of water between soil layers
Fast reservoir baseflow parameter and fast reservoir N for coarse and medium soil regions (4)	Controls quick subsurface stormflow response
Slow reservoir baseflow parameter for coarse and medium soil regions (2)	Controls subsurface baseflow

Calibration results for the 1980-2010 period are summarized in Table 3-11. Additional model metrics have been provided:

- Percent bias, which indicates the overall tendency to over- or under- predict flows (0 = perfect)
- Root mean square error, which summarizes performance in units of m3/s (0 = perfect)

Table 3-11 Model performance statistics summary for calibration basins 1980-2010.

WSC Gauge Name	NSE	% Bias	RMSE
Coldstream Creek above Municipal Intake	0.77	-16.8	0.2
Vaseux Creek above Solco Creek	0.82	-3.3	0.73
Whiteman Creek above Bouleau Creek	0.74	-25.1	0.64
Okanagan Lake Inflows	0.85	18.3	13.5
Kalamalka Lake Inflows	0.71	25.3	1.2

Calibration results in Table 3-11 indicate relatively high NSE values for all of the calibration targets; NSE values at or near 0.8 are generally indicative of a skillful hydrologic model. In particular, the Okanagan Lake inflows, which are likely the most reliable indicator of large-scale performance, showed a very strong result of 0.85. Percent bias results indicate a divide in bias between the calibration subbasins and the inflow calibrations. It was expected that the reservoir inflows would have a positive bias for the entire year because water demand is assumed negligible during the freshet and thus not included within the model. Due to the focus of this model on peak flows, this summer bias in inflows was not considered a significant issue. The simultaneous negative bias at the calibration subbasins (Whiteman, Vaseux and Coldstream Creek) indicated optimization for both inflows and subbasins was a balance between the two observation scales.

The hydrographs for the three calibration basins and lake inflows are shown graphically in Figure 3-7. A single example year is also shown in Figure 3-8, which indicates a good reproduction of the annual freshet hydrograph, and close match of the peak flow for all basins. The positive bias is visible in the falling limb of the inflow hydrograph for both Kalamalka and Okanagan Lake. The over-sensitivity to fall storms for Coldstream Creek is apparent but is not relevant for the ultimate purpose of this model.

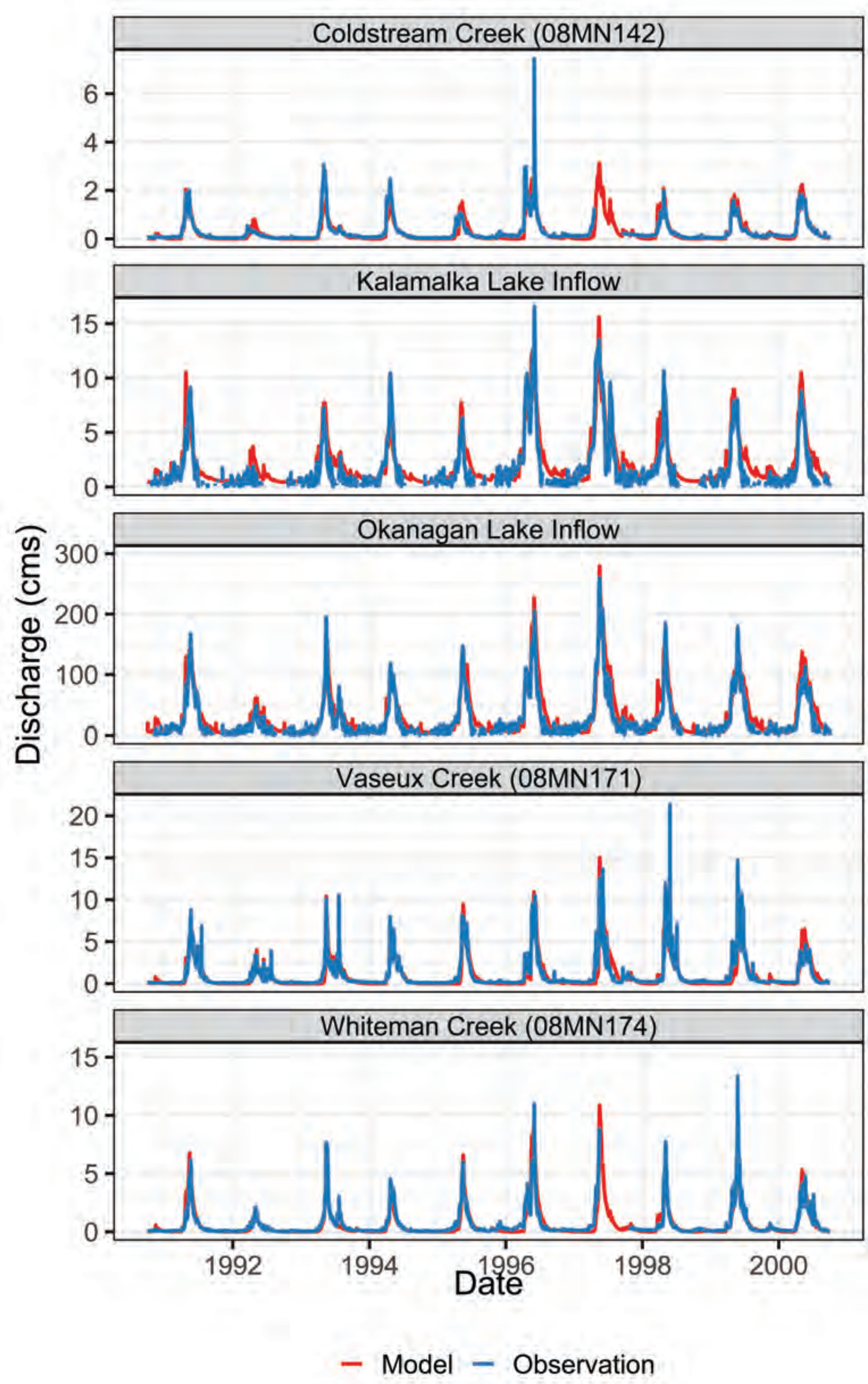


Figure 3-7 Calibration basins and Okanagan and Kalamalka Lake inflows (1990 - 2000).

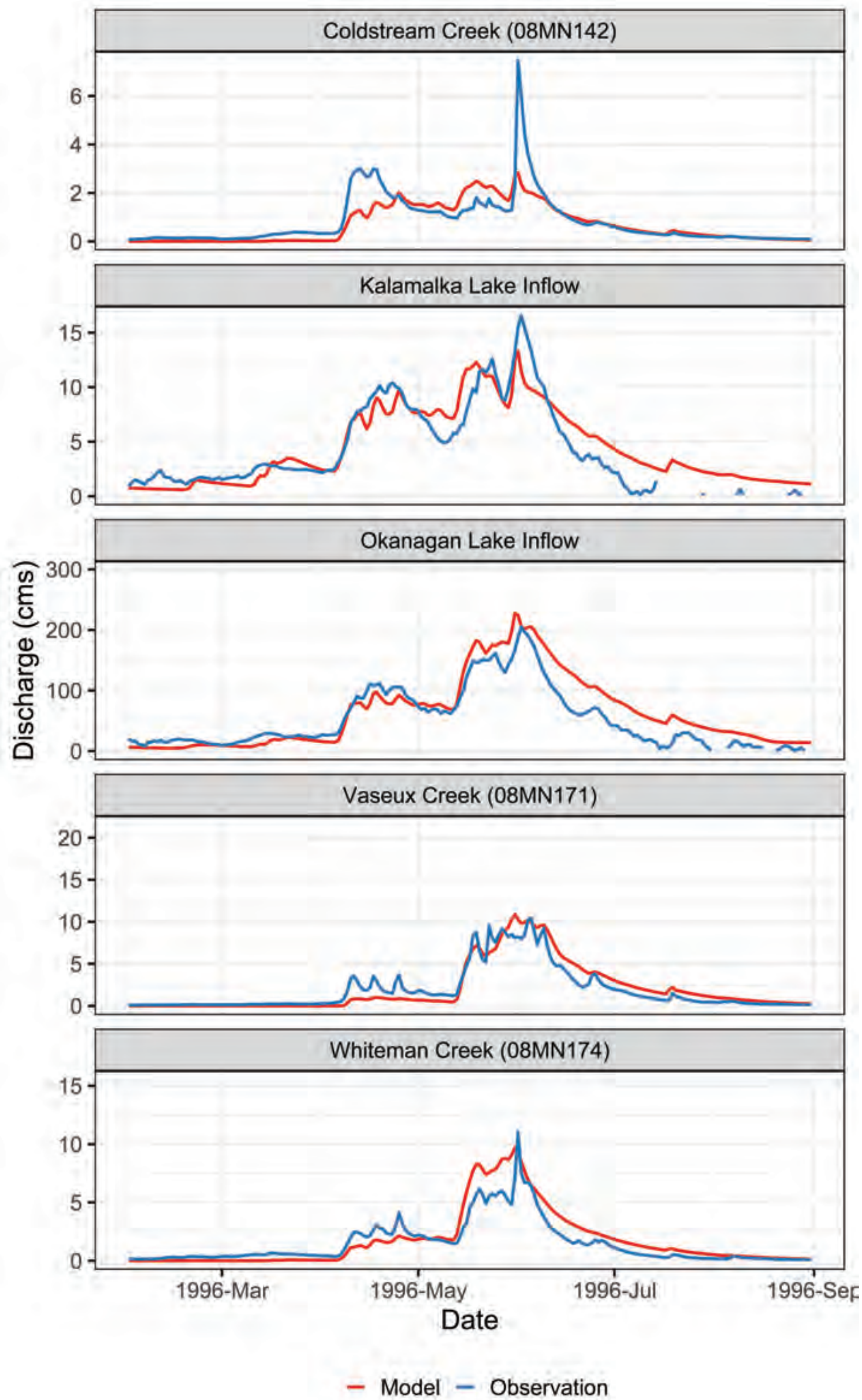


Figure 3-8 Calibration basins and Okanagan and Kalamalka Lake Inflows (Feb-1999 to Sep-1999). Note that observed (calculated inflows) include a 5-day rolling mean filter and removal of negative values to remove noise from calculations.

Along with streamflow observations, observations of snow water equivalent (SWE) from the BC Ministry of Environment were used to assess model performance as 'soft' calibration targets (i.e. not through direct calibration). The BC Ministry of Environment (MOE) collects snow observations, typically at elevations between 1,500 and 2,000 m, both manually (snow courses) at the beginning of each month, and through automated snow pillow weighing gauges. The snow survey locations used for the ORB model are summarized in Table 3-4. These stations were also used to generate the model forecast as the RFC also uses these stations.

A comparison of snow output from the model and the BC MOE observations is shown in Figure 3-9. Simulation results for the HRU overlapping the location of the snow observations were compared directly to observations when available. Note that in some cases the manual snow course and automated snow pillow are nearby but are not at the same location. As such, they may fall on different HRUs. Additionally, the Silver Star mountain snow course is located just outside the ORB, so no coincident HRU exists. Therefore, the nearest HRU to the mountain was used; this may result in a greater difference between 'real' elevation and HRU elevation than the other sites.

The performance at the three unregulated calibration basins is also supported by strong performance in modelling snow accumulation and melt at the snow survey and snow course sites (Figure 3-9). The maximum accumulation and melt timing are modelled well for most sites, with slight under predictions in the mid 90s for Silverstar. The Oyama Lake and Isintok Lake stations show slight over prediction, which may be an indicator of local scale effects on that survey site that are not captured by the scale of this model.

Skillful reproduction of the snow accumulation and melt is important for hydrologic prediction; however, in this case it is also important for the ability to emulate the seasonal forecasts in the ORB model. As mentioned previously, snow survey results are a primary predictor for the monthly water supply forecasts for the Okanagan.

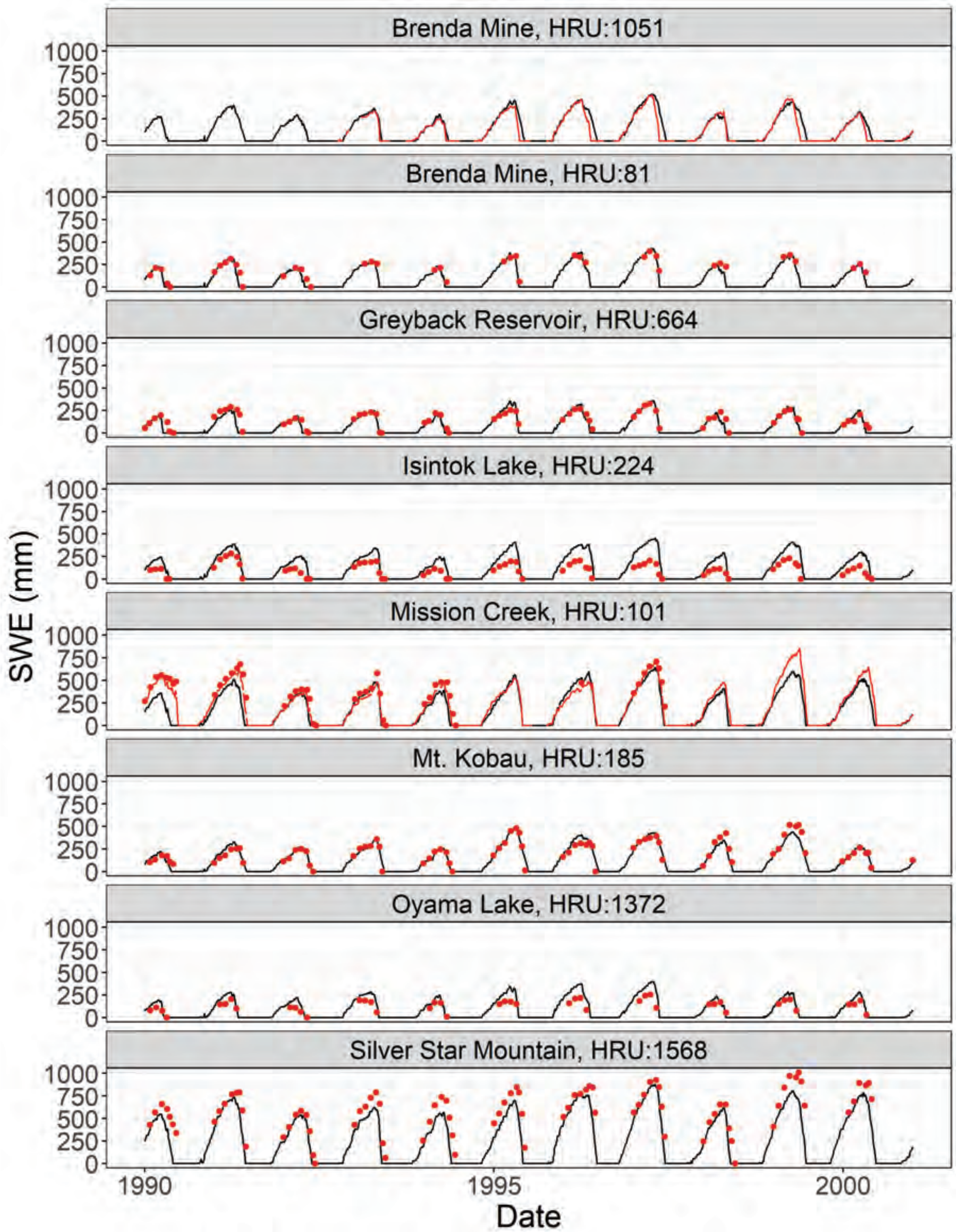


Figure 3-9 Snow model output for the middle calibration period. Red dots indicate manual snow surveys. Red lines indicate automated snow pillow output.

Once the natural portions of the ORB were calibrated, focus shifted to the representation of the basin regulation. Rather than formal calibration, the basin rules were manipulated manually to best emulate the human operation of the system in cooperation with the FLNRORD Okanagan reservoir operator, Shaun Reimer. Additionally, direct calibration was not possible because operations rules changed over time, with the current recommendations not being implemented until 2012. Thus, optimizing performance on historical data was not the ideal way to ensure accurate simulation of future operations.

The agreed regulations to best match the current regulations are summarized in Table 3-13. Figure 3-10 shows the modelled lake stages compared to observed lake levels for Okanagan and Kalamalka/Wood lakes. Results show fairly strong performance; in cases where Raven over or under predicts lake levels, the reason is typically because real operations caused the lake to be either higher or lower than the present-day guidelines would suggest. For example, in Kalamalka and Wood Lake in 1997/98, the lake was not drawn down as low as present day regulations would suggest, thus the observed levels were higher than the modelled. This situation appeared fairly common in Kalamalka/Wood Lake, often in the past the lake was not drawn down as far as current regulations would suggest. This may be due in part to an inability to achieve enough outflow onto Vernon Creek to achieve target levels in Kalamalka/Wood Lake. During low lake levels, only very low outflows are achievable from the lake due to negligible head loss from Kalamalka Lake into Vernon Creek (Shaun Reimer, FLNRORD, pers. Communication, 2020). A future recommendation is that the outflow structure from Kalamalka Lake to Vernon Creek is evaluated to ensure that sufficient outflow can be achieved.

Variations in the drawdown levels (particularly visible on Okanagan Lake, e.g. 1997/98) are due to the water supply forecasts. When larger snowpacks exist mid-winter, a larger inflow is expected, and the reservoir is drawn down lower prior to the onset of the freshet.

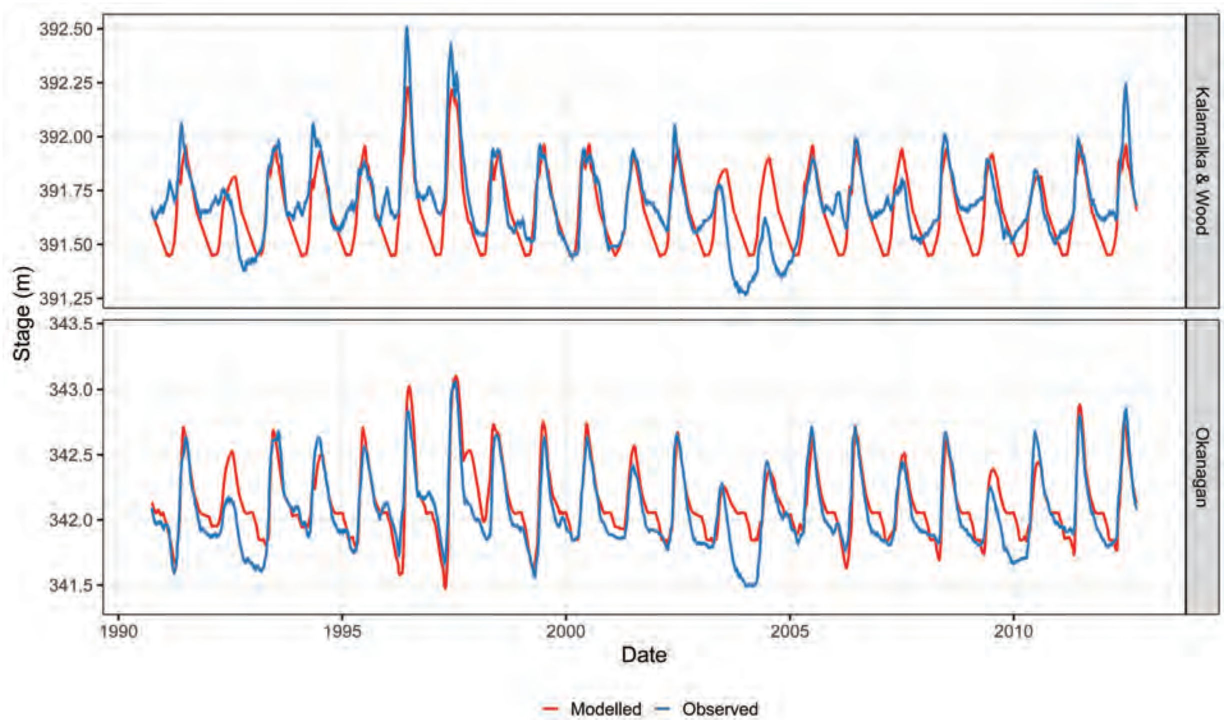


Figure 3-10 Calibrated lake stages at Okanagan Lake and Kalamalka/Wood Lake.

While reservoir levels on Okanagan and Kalamalka/Wood Lakes were modelled satisfactorily, the reservoir releases, particularly from the Okanagan Lake dam at Penticton typically did not follow the actual historical releases and could not realistically be expected to do so. Historical releases are dependent on operator decisions, which encompass logistical reasons (e.g. weekends, allocation of resources, and more) along with following within the release guidelines. Additionally, model releases would be higher during low flow periods. As noted previously, the reservoir extraction and water demand were not included in this model; this excess water was removed and forced downstream during low flow periods. Thus, the modelled releases from the lake are best considered as a realistic situation that could have happened rather than a reproduction of what actually happened. This release scenario also had implications for Skaha, Vaseux and Osoyoos Lake, and was one reason that led to the development of the 'gates open' scenario for determining flows along the Okanagan River (described in the Reservoir Representation section).

Model results for Ellison lake are difficult to interpret for a number of reasons, primarily a lack of data during the calibration period. An Okanagan Nation Alliance (ONA) data logger has been running in recent years. However, these observations occur mostly after the end of the model forcing data, 2012. A WSC gauge existed in the 1970s; however, it is unclear how representative the WSC gauge data is of current conditions; some observations from this period indicate water levels higher than the Lidar measured flood level of 2017. This arouses suspicions in those observations, as major flooding occurred around Ellison Lake in 2017. Further, it is apparent that Ellison Lake levels are heavily influenced by releases from Swalwell (Beaver) lake. At the time of this report, a release schedule for Swalwell Lake was unavailable. A future work recommendation is to obtain (or develop) a detailed plan for operation of releases from Swalwell Lake; this will both help for planning on Ellison Lake and on Swalwell Lake itself, as unscheduled spilling of Swalwell Lake could cause flooding on Ellison Lake.

Model Validation

The Raven model validation approach focused on internal validation (i.e. performance on non-calibration basins) rather than a temporal split sample approach. This method was deemed more useful than the split sample approach because it is difficult to disentangle variations in forcing data (temperature and precipitation) quality over time with variations in model performance. Only the three basins identified in Table 3-11 were used for calibration, leaving all other basins for spatial validation. Figure 3-11 and Figure 3-12 show basins selected for validation purposes. These basins were selected for validation as it was determined they were not so impacted by regulation as to alter peak flows; some subbasins did display flow regulation in the low flow periods.

Due to variable observation times, one group for 1975 to 1985 and one group for 1990 to 2000 is displayed. The performance statistics for these basins are summarized in Table 3-12. The performance for larger basins is mostly maintained but performance begins dropping off for smaller basins. This is expected since dominant hydrologic processes change with scale and the focus of the model development was on capturing processes in the larger basins. Overall, internal validation was quite strong, indicating that the regional calibration parameter transfer was largely successful. In the cases with poor NSE results, this can be most often attributed to either a small subbasin (e.g. Clark Creek, Camp Creek, Greata Creek) or a subbasin with substantial impacts of regulation (e.g. Peachland Creek).

Table 3-12 Model performance statistics for select validation basins. Time period indicated in table notes.

WSC Gauge Name	Drainage Area (km^2)	NSE	% Bias	RMSE
Clark Creek near Winfield[1]	15.3	0.02	-90.0	0.18
Equesis Creek near the mouth[1]	199	0.39	-61.0	0.79
Mission Creek above Pearson Creek[1]	233	0.79	-9.31	2.44
Peachland Creek at the mouth[1]	150	-10.41	89.7	0.84
Powers Creek at the mouth[1]	144	0.68	-0.73	0.76
Shingle Creek at the mouth[1]	308	0.67	7.71	0.71
Trepanier Creek at the mouth[1]	254	0.69	14.9	0.88
Trout Creek at the mouth[1]	764	0.26	56.6	3.47
Belgo Creek below Hilda Creek[2]	70.7	0.59	-45.0	0.59
B.X. Creek above Vernon intake[2]	55.7	0.72	-2.80	0.31
Camp Creek at the mouth near Thirsk[2]	34.6	-0.17	62.6	0.30
Greata Creek near the mouth[2]	40.7	-3.18	154	0.37
Mission Creek near East Kelowna[2]	795	0.83	-0.71	4.27
Shatford Creek near Penticton[2]	101	0.66	16.4	0.46

1. For 1975 – 1985.
2. For 1990 – 2000.

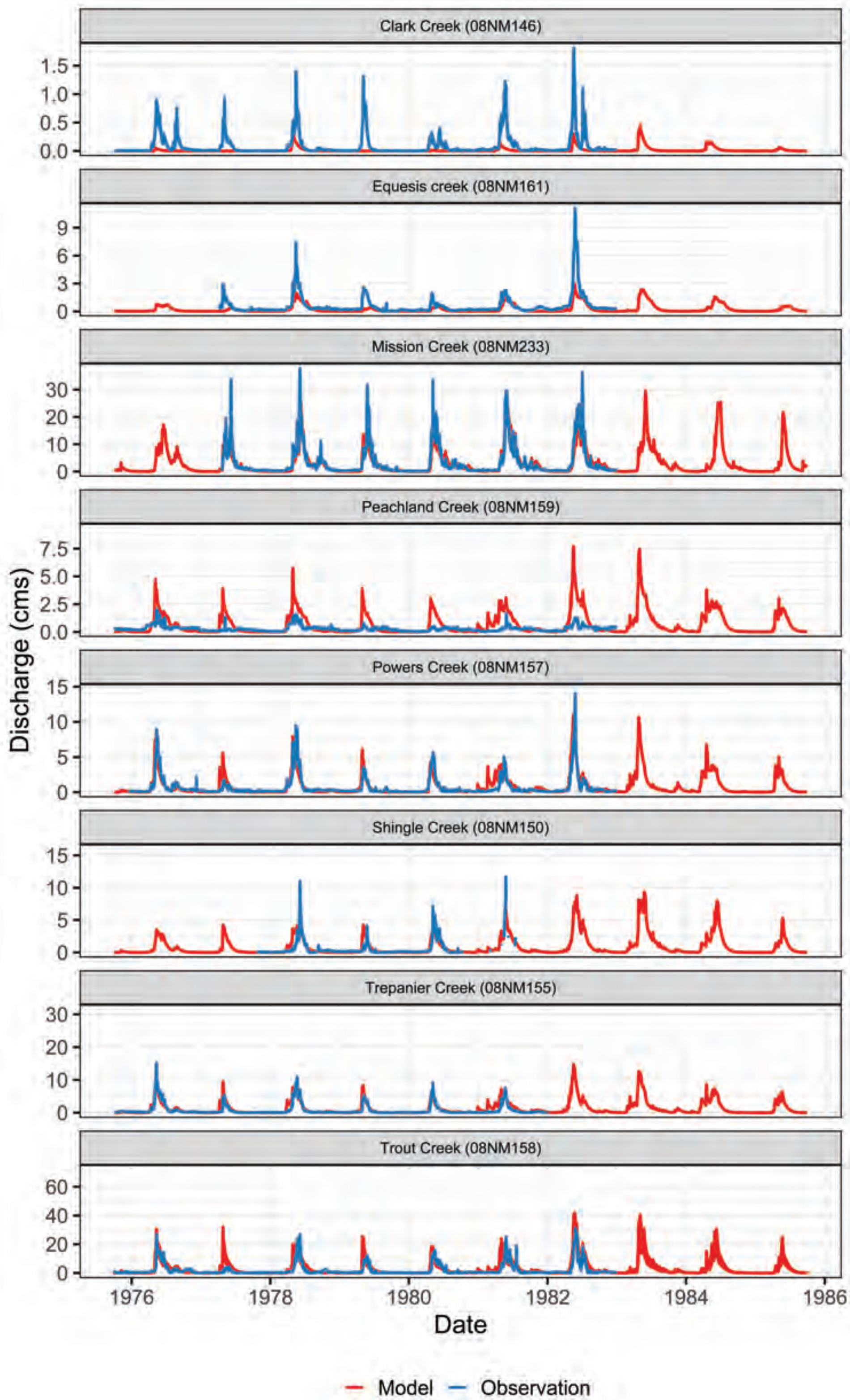


Figure 3-11 Select basins for spatial validation (1975 - 1985).

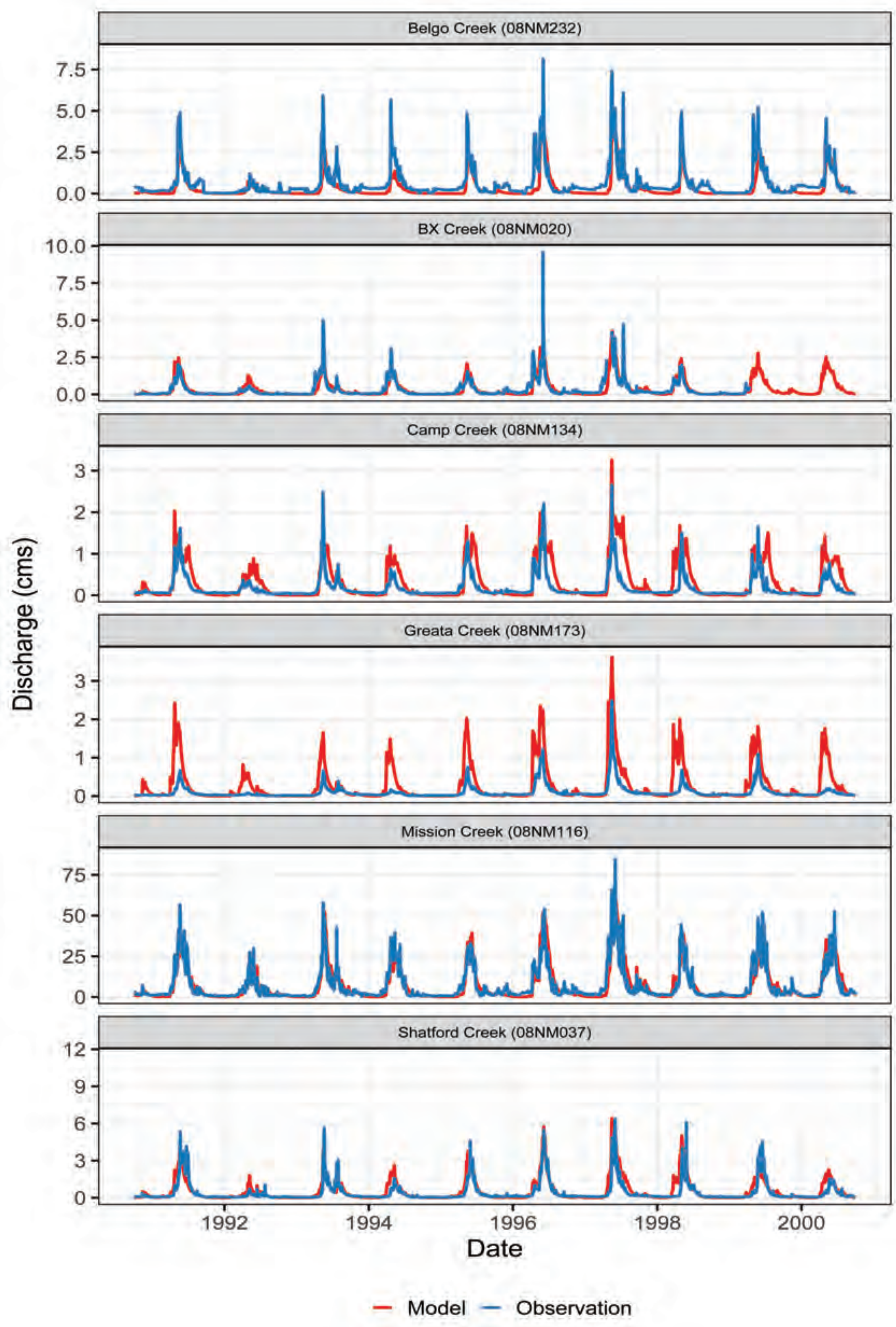


Figure 3-12 Select basins for spatial validation (1990 – 2000).

Reservoir Representation

In Raven, surface water bodies identified as lakes are handled differently from those identified as reservoirs. Table 3-2 describes water bodies explicitly represented as managed reservoirs. All other large surface waterbodies were represented with a linear lake release wherein lake storage and release are lumped into a single unit per subbasin. The reservoir operations in the model had to be simplified and made consistent for the entire simulation period. This was done in close consultation with Shaun Reimer of FLNRORD.

During model development three model scenarios were developed: the first followed current OLRS Operating Plan and guidelines (AE, 2017b), the second included changes to the OLRS Operating Plan and guidelines to account for future changes to the hydrology in the basin (described in section 3.3.5), and the third provided a more conservative estimate of downstream flows in case upstream dam operations were interrupted.

The three model scenarios are:

1) Standard regulation scenario: All lakes follow set rules for reservoir operation determined when modelling the historical reservoir levels.

2) Future regulation scenario: The regulations from the standard regulation scenario were modified at Kalamalka and Okanagan Lakes to better capture a realistic response in the climate ensembles. This scenario was developed in conjunction with FLNRORD operators.

3) Gates open scenario: The gates of Okanagan Lake and Skaha Lake dam are fully open, and the reservoirs outflows are dictated by rating curves.

The standard and future operations scenarios applied to lake levels on Okanagan Lake and Kalamalka/Wood Lake. As noted in the calibration section, while lake levels could be accurately reproduced on these lakes with the regulation rules, it was not possible to replicate the human operations that occur during reservoir releases. Often, reservoir releases follow more intricate strategies than can be captured in a rule system. For example, when high flows are anticipated from tributaries along the Okanagan River, the reservoir operator has drawn down Skaha Lake ahead of time and used the lake to absorb flows from Okanagan Dam so that they do not coincide with high flows along the canal, and Okanagan River flows can remain as low as possible (Shaun Reimer, FLNRORD, pers. communication, 2020).

In most situations, releases from Okanagan Lake were capped at 78 m^3/s in order to limit downstream infrastructure damage. However, an emergency outflow scenario, developed in conjunction with the reservoir operator, was implemented when lake levels came within 0.40 m of the levels of the beaches on the south shore of the lake in Penticton. At this level (343.47 m, CGVD2013 datum), maximum releases were allowed to increase to 100 m^3/s to help avoid flooding in downtown Penticton (Shaun Reimer, FLNRORD, pers. communication, 2020).

Additionally, operations of Skaha Lake could not be used for production of design flows. Skaha Lake has a very similar capability of both inflow and outflow; thus, the lake levels can in most cases be set at a desired level by the operator (Shaun Reimer, FLNRORD, pers. communication, 2020). Because of this capability, under perfect operation, Skaha Lake would always reach approximately the same maximum level each year.

Because these types of reservoir operations could not be accurately codified within an operations model, and because they should not be relied upon in the future (e.g. perfect operation of Skaha Lake is not a realistic expectation), it was decided that the gates open scenario for the Okanagan River, Skaha Lake and Vaseux Lake was the most conservative and appropriate approach.

The standard and future regulations scenarios also resulted in higher lake levels in Kalamalka, Wood and Okanagan Lake but lower discharges and levels downstream when compared to the gates open scenario. Therefore, to be conservative, the standard and future regulation scenario were applied to everything upstream of Okanagan Lake (including Okanagan Lake itself) and the gates open scenario was applied to everything downstream (with the exception of Osoyoos Lake which is discussed in section 3.3.4).

Table 3-13 summarizes how the lakes were represented for the Standard Regulation and Gates Open scenarios and Table 3-14 shows the monthly varying restrictions for Kalamalka and Okanagan lakes. Ellison Lake is controlled by a simple rock weir, and thus no regulations rules were applied

Note that in the absence of observed hydrometric data or operating rules Ideal, Otter, and Oyama Lake discharge were calculated using a weir coefficient equation. Additionally, Swan Lake used a variable weir height which accounted for the changing number of stop-logs during different times of the year.

The modified rule set for Okanagan and Kalamalka/Wood Lake was developed to result in a more realistic prediction of future reservoir operations when facing climate change in conjunction with the reservoir operator. The changes from Table 3-13 and Table 3-14 include:

- lowering the reservoir targets in fall and winter by 0.20 m at Okanagan lake
- allowing maximum outflows of 78 m^3/s in February, March, and April at Okanagan Lake,
- increasing ramping rates on Kalamalka and Okanagan Lake to the 99th percentile observed rate year-round.
- increasing maximum outflows to 6 m^3/s all year at Kalamalka Lake

Table 3-13 Model lake representation for each scenario.

Lake	Control	Standard Regulation Scenario[1]	Gates Open Scenario[1]
Ellison	Stage-discharge	Developed from WSC and ONA data	
	Stage – volume Stage - area	Bathymetry	
Kalamalka/Wood	Maximum increase and decrease in outlet discharge[2]	From WSC gauge data	N/A
	Maximum outlet discharge	See Table 3-14	N/A
	Minimum outlet discharge[3]	0.085 m^3/s	
	Monthly Reservoir Target	From RFC forecast	N/A
Okanagan	Maximum increase in outlet discharge[4]	From WSC gauge data	
	Maximum decrease in outlet discharge[5]	From WSC gauge data	N/R
	Maximum reservoir stage[6]	343.47 m	N/A
	Maximum outlet discharge	See Table 3-14	N/A
	Minimum outlet discharge	From WSC gauge data	N/A
	Stage – Discharge[7]	N/R	Reported rating equation[13]
	Stage – Volume Stage – Area	N/R	Bathymetry
	Monthly Reservoir Target	From RFC forecast	N/A
Skaha	Stage – Discharge[7]	N/R	Reported rating equation[13]
	Stage – Volume Stage – Area	N/R	Bathymetry
Vaseux	Stage – Discharge[8]	N/R	Empirical rating curve (flow above 45 m^3/s)
	Stage – Volume Stage – Area	N/R	Bathymetry
Osoyoos	Stage – Volume Stage – Area	N/R	Bathymetry
	Monthly Reservoir Target Levels	N/R	See Table 3-7
Swalwell (beaver)	Stage – Discharge (including low level outlet)	Developed from WSC data	

Lake	Control	Standard Regulation Scenario[1]	Gates Open Scenario[1]
	Stage – Volume Stage - Area	Bathymetry	
	Minimum outlet discharge[9]	0.06 m^3/s	
	Minimum stage[10]	1340.08 m	
Swan	Stage – Discharge[11]	3 stoplogs	N/R
Oyama	Stage – Volume Stage - Area	Bathymetry	
Otter	Stage – Volume Stage - Area	Bathymetry	
Ideal	Stage – Volume Stage - Area	Bathymetry	

1. N/R means not relevant to model scenario and N/A means not included in model scenario.
2. 99th percentile of daily discharge differences since 1990 at 08NM065 for Standard Regulation and X for Gates Open.
3. Minimum environmental flow need in Vernon Creek (AE, 2017b).
4. 95th percentile of daily discharge difference at gauge 08NM050 for data after 1990.
5. 5th percentile of daily discharge difference at gauge 08NM050 for data after 1990.
6. Corresponds to 0.4 m below Penticton beach level from Associated Engineering (2012). Beyond this level, emergency outflows of 100 m^3/s are allowed (Shaun Reimer, FLNRORD, pers. Communication 2020).
7. Adapted from BC Environment (1991).
8. Developed from WSC data with discharge greater than 45 m^3/s, Reported flow where lake confluence to Okanagan River begins controlling lake release (AE, 2017b).
9. 5th percentile of flows entering Ellison Lake (08NM162).
10. Zero flow on developed rating curve.
11. Ecora (2019b).

Table 3-14 Monthly varying maximum outlet discharge for Standard Regulation Scenario for Okanagan Lake and Kalamalka Lake.

Month	Maximum outlet discharge (m^3/s)	
	Okanagan Lake	Kalamalka Lake
January	28.3	2.5
February	28.3	2.5
March	28.3	2.4
April	28.3 (78)	4.1
May	78	6.0
June	78	6.0
July	78	6.0
August	78	6.0
September	78	3.9
October	15.6	3.1
November	28.3	2.4
December	28.3	2.0

1. Flows for August and September altered from AE (2017) to account for operation in 1997.
2. Numbers in parentheses are if the forecasted inflow volume is greater than 620 million m^3.

Model Bias Corrections

In the calibration results section, positive bias existed for the calibration to the reservoir inflows. It was expected that this bias was primarily occurring during the low flow periods and did not have an impact on peak flows (or lake levels). This section explores this bias further. As a first step the mean lake inflows (simulated and calculated from observations) were calculated for the date of peak inflow +/- 10 days for Okanagan Lake in order to investigate bias during the freshet (1960-2012)[1]. Results showed a -0.2 % bias. Visual inspection of the data in Figure 3-13 confirms that there is not likely bias during the freshet period on Okanagan Lake.

[1] Model output from the earliest gridded forcings data (pre 1960) indicates a potential for under-representation of basin-wide precipitation, hence we did not include it in these comparisons.

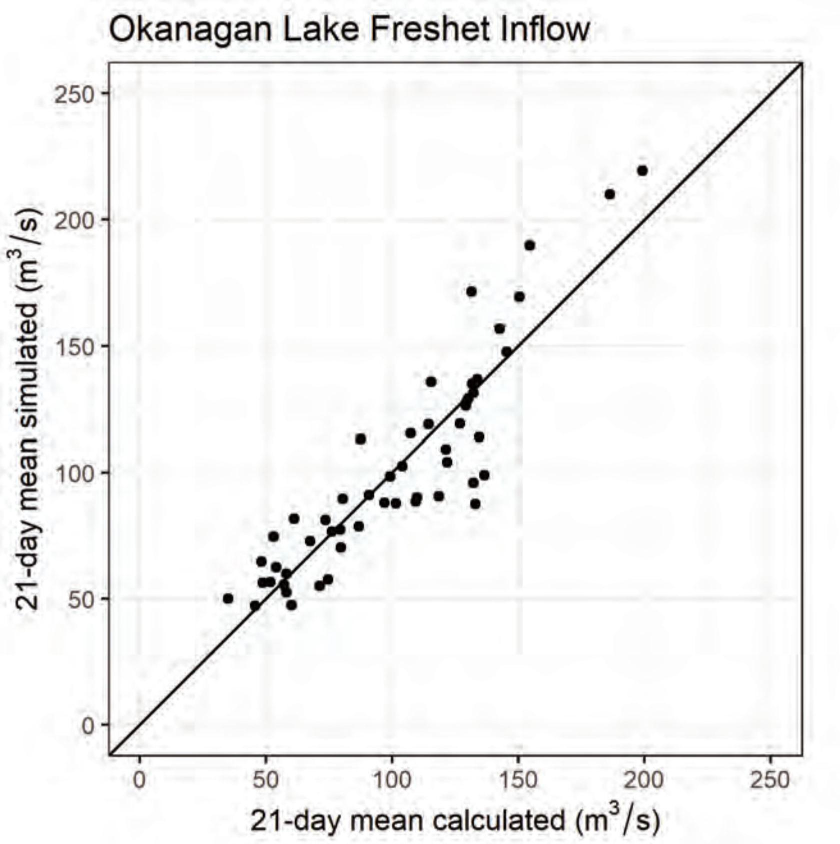


Figure 3-13 Comparison of calculated and observed Okanagan Lake inflow. Values indicate mean 21-day inflow, at the day of the peak +/- 10 days. Black line is a 1:1 line.

In order to investigate bias on the Okanagan River, the Okanagan Lake releases were first over-ridden in Raven with observed outflows[1] from the Okanagan Lake Dam at Penticton. This ensured that the river began its journey at Penticton with perfect accuracy and accumulation could be investigated as the river travelled its length to Osoyoos Lake. The results of this are shown in Figure 3-14. The figure indicates that bias is accumulated along the river, going from 9.5% at Okanagan Falls to 16.5% at Oliver.

There are a number of reasons why this may be occurring, including (but not limited to):

- The significant impact of water demand along this canal, which is unaccounted for in the model.
- The potential for loss of water into the groundwater in the lower fans of tributaries to the river, which is not accounted for in this model.
- A relative lack of calibration data in the southern portions of the ORB

[1] As mentioned in the calibration results, reservoir releases could not be accurately reproduced by the model; hence real observations were the most appropriate choice.

- The impact of side channels to the Okanagan River retaining some water during high flow periods

It is recognized that this bias may have a significant impact on Osoyoos Lake levels, which are dependent on the volume of water that flows into the lake. It was deemed unnecessary to apply a correction to the actual flows along the Okanagan River from Penticton to Osoyoos, as these flows are more peak dependent than volume dependent, and since there is already some uncertainty in the relation of a daily model to instantaneous peaks, a more conservative approach is to leave this data uncorrected. However, the lake levels of Osoyoos Lake were found to be considerably more sensitive to overall volume, and the lack of water demand modelling may have an impact on volume into Osoyoos Lake. The annual % bias for inflows to Osoyoos Lake during the period of observation post-1960 was found to be 23.6%. Thus, we accounted for this bias by applying a 25% (rounding to the nearest 5%) reduction to model inflows to Osoyoos Lake for reservoir level calculations, which are described in the following section.

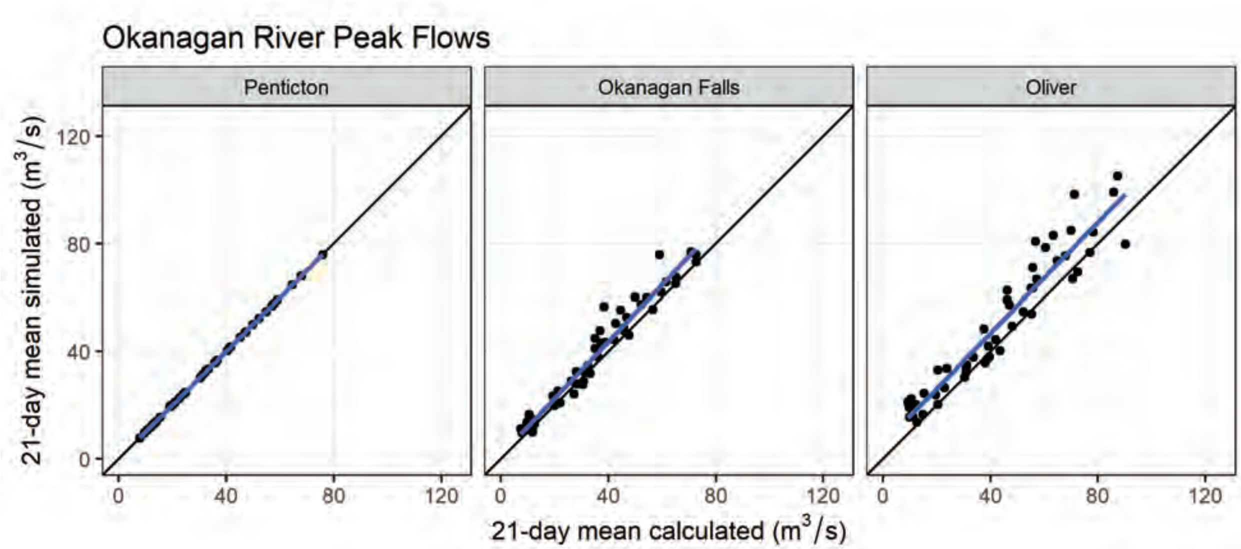


Figure 3-14 Comparison of calculated and observed Okanagan Lake River flows with observation override at Penticton. Values indicate mean 21-day inflow, at the day of the peak +/- 10 days. Blue lines are linear models of the data, black lines are 1:1 line.

3.3.4 Influence of the Similkameen-Okanogan Confluence on Osoyoos Lake Levels

Characterizing flood levels on Osoyoos Lake is greatly complicated by the dependence of Osoyoos Lake outflows on Similkameen River discharges during high flows on the Similkameen. Flood levels on Osoyoos Lake are caused not only by direct inflows, but also by high flows on the Similkameen which impose a backwater control on lake outflows and in extreme situations flow reversals on the Okanogan River below Osoyoos Lake.

As shown in Figure 3-15, the Similkameen joins the Okanogan approximately 5 km downstream from the natural outlet of Osoyoos Lake. While the tributary area of the Similkameen at its confluence with the Okanogan (approximately 9,300 km^2) is comparable to the tributary area of the Okanogan at the outlet from Osoyoos Lake (approximately 8,100 km^2), the Similkameen generates considerably larger peak flows due to greater winter snow accumulation and absence of lakes similar to those on the Okanagan which act to attenuate peak flows. High freshet period flows on the Similkameen result in high water levels at the confluence with the Okanogan which in turn impose a backwater influence on lake outflows.

Figure 3-15 The Similkameen/Okanogan River confluence downstream from Osoyoos Lake.

Outflows from Osoyoos Lake are managed in part through operation of Zosel Dam located approximately 2.5 km downstream from the natural outlet of Osoyoos Lake. The original Zosel Dam was constructed in 1927 to provide a millpond for delivery of logs to the Zosel Mill. The original wooden structure deteriorated over the years and by the 1970's was in a state of serious dilapidation, with partial failures of the structure occurring in 1974 and 1975. Construction of the present dam began in 1986 and was essentially completed in 1987.

In hydraulic design study reports for the present structure (Acres International Ltd., 1986), it is stated that:

> *"The proposed structure is not intended for flood control but for regulating the Osoyoos Lake level between 909.0 feet and 913.0 feet under normal conditions. Compared to the present Zosel dam, the proposed structure will not alter flood levels caused by Similkameen backwater flows but will allow more operating flexibility and greater discharge capacity for Okanogan River flows".*

The two largest events on record in terms of backwater effect from the Similkameen are the freshets of 1948 and 1972. The greatest reported flow reversal on the Okanogan River below Osoyoos Lake was for a daily average discharge of -64 m^3/s (-2,270 ft^3/s) in the 1948 freshet. Backwater effects during the 1972 event produced a minor flow reversal and reduced the mean daily outflow from Osoyoos Lake to nearly zero. The 1972 event also resulted in the highest level for Osoyoos Lake (279.64 m CGVD 2013 or 917.06 ft NGVD 1929) since records began in 1928.

Additionally, the USGS reports a peak water level in 1894 (i.e. before the construction of Zosel Dam and outside the period of systematic record) of 280.17 m CGVD 2013 (918.8 ft NGVD 1929). The 1894 freshet was an extreme historic flood event throughout southern BC and the US Pacific Northwest. The peak flow for the 1894 freshet on the Similkameen River at Nighthawk was estimated by the US Army Corps of Engineers as 1,416 m^3/s (50,000 ft^3/s) and likely also resulted in a large flow reversal on the Okanogan River below Osoyoos Lake.

The effects of high Similkameen flows on Osoyoos Lake levels and outflows are shown for illustrative purposes in Figure 3-16 for the 1972 freshet. The top panel of Figure 3-16 shows the extremely high flows reached on the Similkameen during the freshet, the middle panel shows flows for the Okanagan River at Oliver (inflows to Osoyoos Lake) and at Oroville (outflow from Osoyoos Lake), and the bottom panel shows the Osoyoos Lake water surface elevations. The figure illustrates the effect of high Similkameen flows on inhibiting lake outflows and hence raising lake levels.

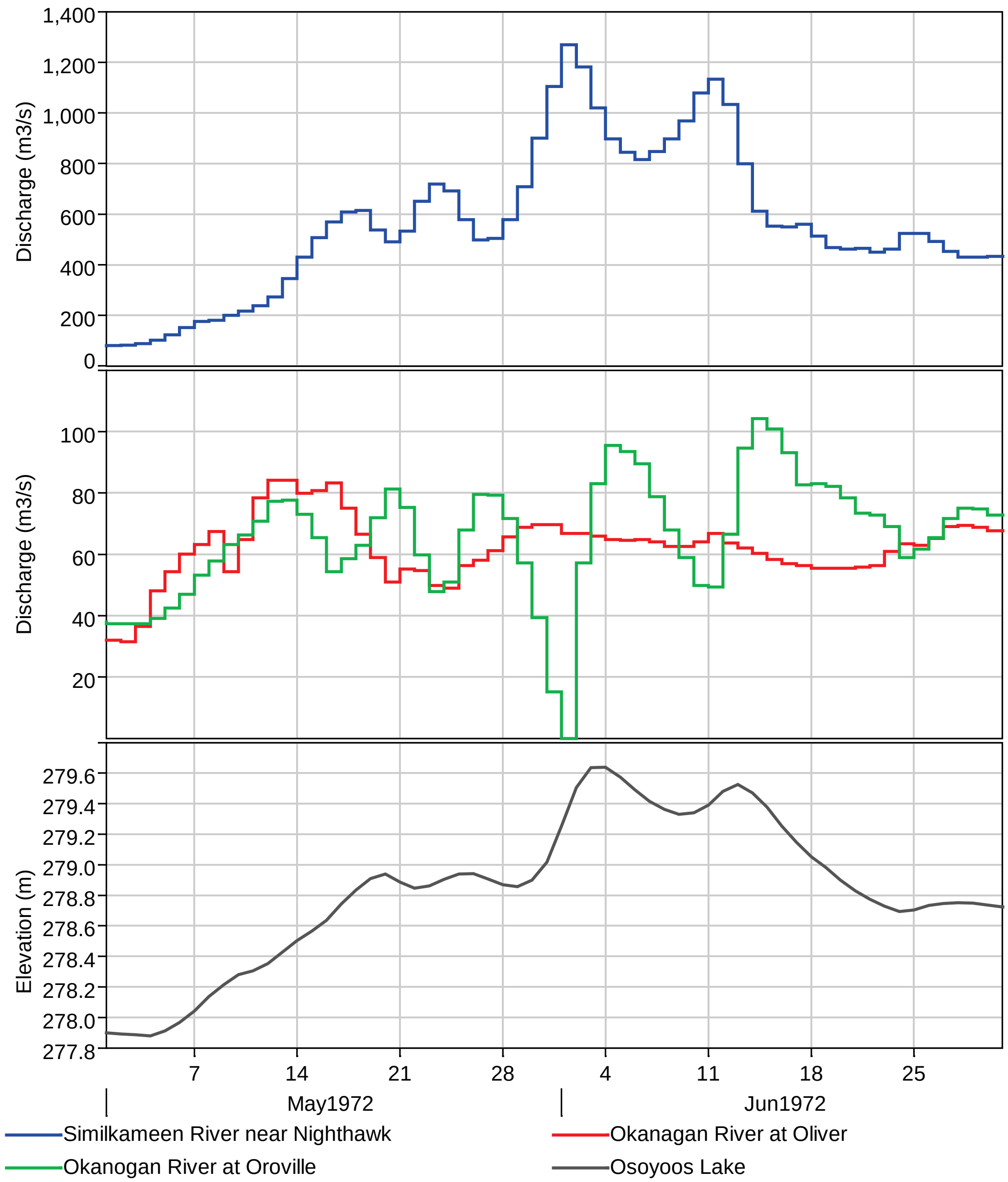


Figure 3-16 Illustration of backwater effects from high Similkameen River flows in the 1972 freshet.

Several studies have attempted to model the backwater effects of high Similkameen River flows on Osoyoos Lake outflows (i.e. Okanogan River flows) and Osoyoos Lake levels.

McNeil (1974) describes a method for predicting the outflow from Osoyoos Lake under Similkameen backwater conditions which required only knowledge of the Similkameen flow and the level of Osoyoos Lake. The model produced reasonably accurate simulations of Osoyoos Lake levels for the spring freshets of both 1948 and 1972. However, the relationships developed by McNeil are almost certainly out of date due to changes in channel geometry around the Similkameen/Okanogan confluence and on the Okanogan River itself, and the reconstruction of Zosel Dam and associated work.

Modelling of conditions at the Similkameen/Okanogan confluence was reported by Northwest Hydraulic Consultants (1987) as part of a flood control feasibility study for a proposed multi-purpose dam on the Similkameen River approximately 10 km upstream from the confluence with the Okanogan River. A three-dimensional backwater relationship was developed to predict discharge on the Okanagan River at Oroville (outflow from Osoyoos Lake) given Osoyoos Lake elevation and Similkameen River elevation at the confluence with the Okanogan River. The Similkameen River elevation was in turn determined from a stage-discharge rating for the Similkameen River at Oroville. These relationships were incorporated into a SSARR hydraulic model and calibrated to reproduce, with reasonable accuracy, conditions in the freshets of 1948, 1972 and 1984. As with McNeil (1974), these relationships are likely now outdated, and the SSARR model used to test the relationships cannot be located.

The most recent work to quantify the backwater relationship is that undertaken by Summit Environmental Consultants (2010) as part of a comprehensive evaluation of factors affecting high Osoyoos Lake levels. Summit developed a multiple regression relationship to estimate Okanogan River outflows under backwater conditions based on Osoyoos Lake levels and Similkameen River discharges. The relationship was originally reported in English units. After conversion to metric units and for lake elevations in CGVD 2013, the backwater relationship is as follows:

$$Q_{OKANOGAN} = 64.616 * (WL_{OSOYOOS} - 0.119) - 0.14 * Q_{SIMILKAMEEN} - 17860.2 \qquad \text{Eqn. 1}$$

where:

$Q_{OKANOGAN}$ = Okanogan River discharge under backwater conditions (m^3/s)

$WL_{OSOYOOS}$ = Osoyoos Lake water level (m CGVD 2013)

$Q_{SIMILKAMEEN}$ = Similkameen River discharge (m^3/s)

This regression relationship was based on data under backwater conditions from the period 1988-2008 (i.e. since the reconstruction of Zosel Dam). The highest daily average flow on the Similkameen in the period considered was approximately 745 m^3/s (26,300 ft^3/s). By comparison, the peak flow in the 1972 flood of record for the Similkameen near Nighthawk was 1,270 m^3/s (44,800 ft^3/s).

Additional testing of Summit's regression relationship, discussed further below, showed good results for simulation of peak lake levels in 1972. As a result, and considering that Summit's work was quite recent, the relationship shown in Equation 1 above was adopted for the current study.

The backwater relationships summarized above rely on the availability of discharge data for the Similkameen River near Nighthawk. While a good record of observed historical discharge is available, no Similkameen River discharge data are available for alternative historical realizations or for future scenarios under climate change consistent with those developed under the current project for the Okanagan River Basin upstream from its confluence with the Similkameen.

For the current project, flows for alternative historical realizations and future scenarios under climate change were simulated for the Okanagan River Basin using the Raven model described in section 3.3.3. However, resources were not available to extend Raven hydrologic modelling to the Similkameen River basin, hence an alternative approach was needed to estimate Similkameen flows under those scenarios.

Several alternatives to synthesizing daily Similkameen River discharges were explored based on regression of observed Similkameen flows against simulated flows for the historic observational period (1946-2012) for various subbasins, or at various points, in the Okanagan River Basin Raven model. These included regressions against simulated Okanagan Lake inflows (i.e. before the attenuating effects of routing through Okanagan Lake are introduced) and against simulated flows for several subbasins on the western side of the Okanagan River Basin, bordering the Similkameen and hence having climatic forcings similar to those that would be experienced by the Similkameen.

The approach finally adopted was to rely on regression of observed Similkameen River daily discharge against simulated daily flows for the historic observational period (1946-2012) from Shatford Creek. Shatford Creek is a relatively small sub-basin (101 km^2) on the western side of the Okanagan River Basin. A simple linear regression forced through the origin (R^2 = 0.73) gave the relationship:

$$Q_{SIMILKAMEEN} = 131.4 * Q_{SHATFORD} \qquad \text{Eqn. 2}$$

where:

$Q_{SIMILKAMEEN}$ = Similkameen River daily discharge (m^3/s)

$Q_{SHATFORD}$ = Shatford Creek daily discharge (m^3/s)

This relationship, based on the historic observational period, was assumed to apply to both alternative historical realizations and future climate scenarios.

A two-step approach was adopted for modeling Osoyoos Lake levels under both historic and future scenarios. Regulation of Osoyoos Lake was first modeled in a similar manner to other lakes in the system using the target water levels from Table 3-7 to produce time series of daily Osoyoos Lake outflow and water levels with no allowance for Similkameen backwater effects. The resulting time series of lake outflows and lake levels were then post-processed and modified to account for Similkameen backwater effects as follows:

1) When Similkameen River flows exceeded the threshold above which backwater effects are normally felt (283 m^3/s or 10,000 ft^3/s), Osoyoos Lake outflows were recomputed using the relationship from Equation 1 above, and lake levels were adjusted accordingly (increased) to maintain mass balance.

2) Once Similkameen River flows dropped back below the 283 m^3/s backwater threshold, lake outflows were increased following the discharge rating for Zosel Dam with gates fully open (Figure 3-17) until the lake level dropped to its target elevation, at which point operations reverted to regulation without backwater effects. (The gate fully open rating was adopted

under the assumption that the lake would be drawn down to its target elevation as quickly as possible).

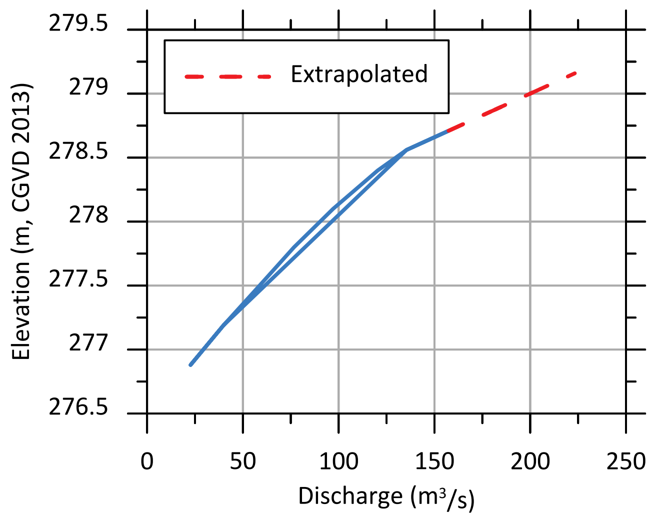


Figure 3-17 Osoyoos Lake elevation-discharge rating, Zosel Dam with gates fully open (adapted from Summit [2010]).

The use of Shatford Creek as a surrogate for Similkameen River flows and the approach to modeling the effects of backwater were tested by simulating Osoyoos Lake levels with various combination of observed and simulated data for the period 1961-2012.

Testing of the backwater modeling approach was performed for the period 1961 -2012 using observed flows from the Okanagan River at Oliver (WSC gauge 08NM085) as inflow to Osoyoos Lake (ignoring the small incremental inflow downstream from the Oliver gauge) and observed flows for the Similkameen River near Nighthawk (WSC gauge 08NL022/USGS gauge 12442500). Simulated and observed lake levels (Figure 3-18) show good agreement in the peak for the 1972 freshet, which produced the highest lake level in the systematic record. Results for other events are somewhat variable with excellent simulation results in some years of observed high lake levels (e.g. 1997) and undersimulation in other years (e.g. 1974). Results for the full period of simulation can be seen in the digital files accompanying this report.

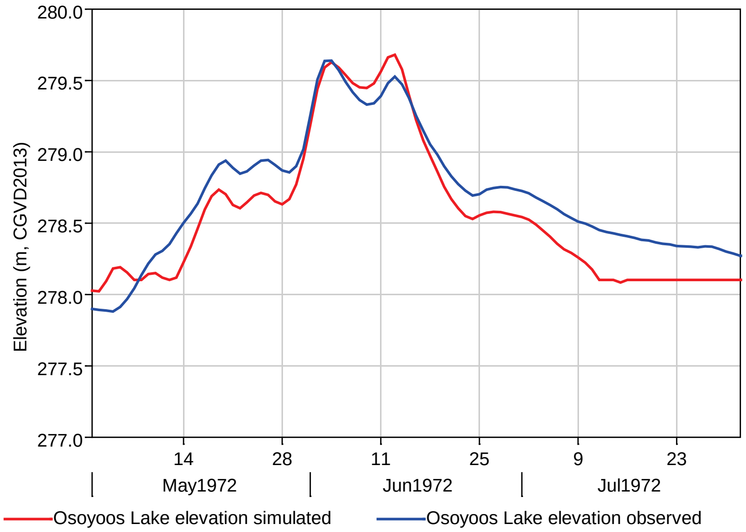


Figure 3-18 Simulated and observed Osoyoos Lake levels, May-July 1972. (Simulated based on observed Osoyoos Lake inflows and observed Similkameen River flows).

Testing of the use of Shatford Creek as a surrogate for the Similkameen River was also performed for the period 1961 -2012 using observed flows from the Okanagan River at Oliver (WSC gauge 08NM085) as inflow to Osoyoos Lake (ignoring the small incremental inflow downstream from the Oliver gauge) and synthesized Similkameen River flows derived from Equation 2 with simulated Shatford Creek flows. Simulated and observed lake levels (Figure 3-19) again show good agreement in the peak for the 1972 freshet. Results for other events are variable with a tendency to undersimulation of peak lake levels in the early part of the simulation period and oversimulation in the later part. Results for the full period of simulation can again be seen in the digital files accompanying this report.

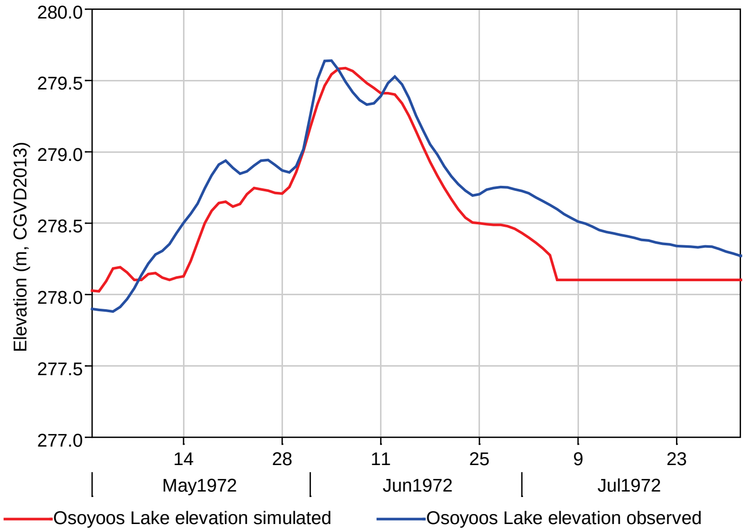


Figure 3-19 Simulated and observed Osoyoos Lake levels, May-July 1972. (Simulated based on observed Osoyoos Lake inflows and synthesized Similkameen River flows).

A test was also conducted using simulated Osoyoos Lake inflows from the Raven model and observed Similkameen River flows. Initial simulation results (see Figure 3-20 for the 1972 freshet) showed consistent oversimulation of lake levels. Further investigation demonstrated that this was a result of oversimulation of inflows to Osoyoos Lake. As discussed earlier under section 3.3.3, this bias was attributed to several factors including the following:

- Simulated flows do not account for abstractions for irrigation or other consumptive water uses in the basin.
- Simulated flows do not consider losses from the Okanagan River (to either relic side channels or the groundwater) or losses in the alluvial fans of its tributaries to groundwater.
- Modelled reservoir operations do not account for operations at upstream dams between Okanagan Lake and Osoyoos intended to reduce peak flows along the river and inflows to Osoyoos Lake (and hence control maximum lake levels).

To account for these effects a bias correction (a multiplier of 0.75) was applied to simulated inflows to Osoyoos Lake for all historical and future scenarios. Simulation results for the 1972 freshet with and without this bias correction are shown in Figure 3-20 and Figure 3-21 respectively. With bias-corrected simulated inflows, peak lake levels for the largest freshet events in the simulation period (1972, 1974 and 1997) tend to be slightly oversimulated (see Table 3-15). However, given the various sources of uncertainty in this analysis, we consider some certain degree of conservatism in simulated lake levels to be appropriate.

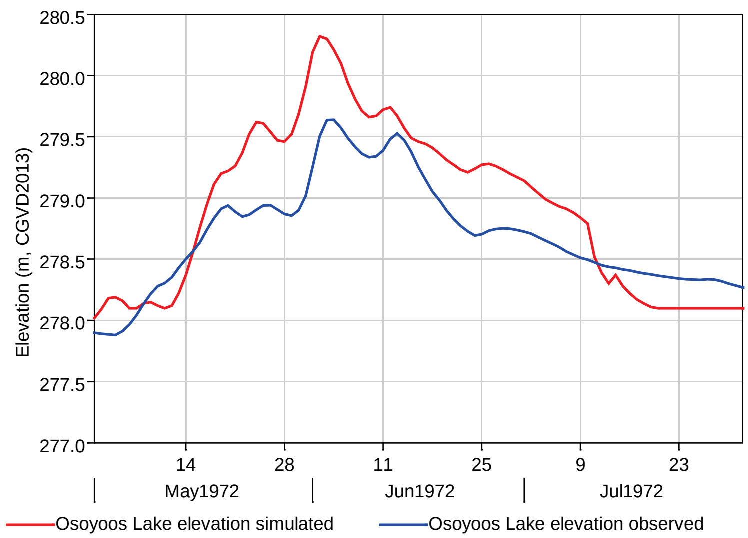


Figure 3-20 Simulated and observed Osoyoos Lake levels, May-July 1972. (Simulated based on simulated Osoyoos Lake inflows and observed Similkameen River flows).

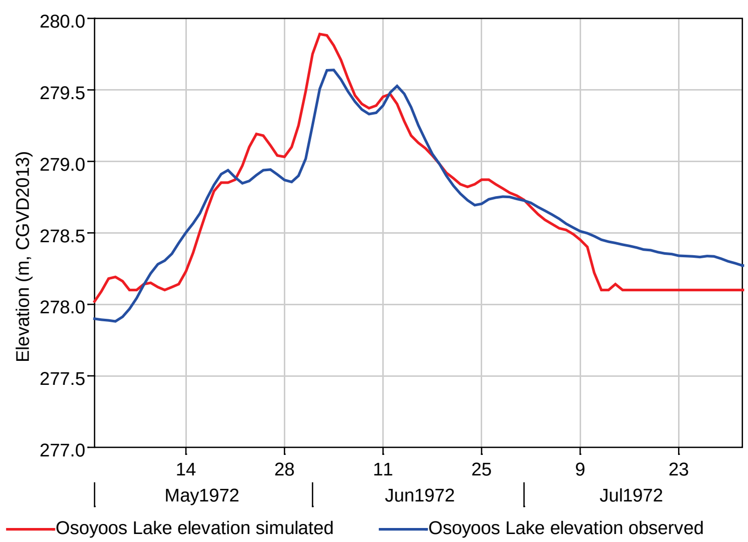


Figure 3-21 Simulated and observed Osoyoos Lake levels, May-July 1972. (Simulated based on bias-corrected simulated Osoyoos Lake inflows and observed Similkameen River flows).

Table 3-15 **Simulated and observed peak Osoyoos Lake levels. (Simulated based on bias-corrected simulated Osoyoos Lake inflows and observed Similkameen River flows).**

Year	Peak Osoyoos Lake Level		Difference (m)
	Observed (m CGVD 2013)	Simulated (m CGVD 2013)	
1972	279.64	279.89	+0.25
1974	279.24	279.44	+0.20
1997	279.04	279.10	+0.06

3.3.5 Ensemble Simulations

This section describes the results of running the 50 climate ensemble members through the Raven model, each running from 1950:2100. In total, 7500 (50*150) years of potential historical and future weather were simulated. Section 2.6 showed that the CanLeadV1 ensemble climate data projects an expected increase in temperature and an increase in precipitation in all periods except the mid/late summer for the ORB. These increases in temperature with increases in winter precipitation mean that a substantially larger amount of the increased winter precipitation will fall as rain instead of snow. This changing distribution is shown over time in Figure 3-22. In turn, the total amount of snow on the ground is expected to decrease dramatically in winter, and complete snow disappearance may occur up to a month earlier, on average by 2100 (Figure 3-23).

This shift in precipitation amount, timing, and type, along with increased temperatures, is likely to have a substantial impact on the timing of peak reservoir inflows and future reservoir operations. The current forecasting and reservoir operations system assume that peak reservoir inflows will occur generally at the same time of year for the major lakes of the ORB. Figure 3-24 shows that the peak inflow date is likely to continue to shift earlier in the year for the rest of the century. By the end of the century, model results indicate that a fall/winter peak inflow to Okanagan Lake may be possible, though still uncommon. This shift in inflow timing has major implications for the reservoir management system, which, due to the size of the reservoirs and low outflow capacity, is dependent on forecasting flows for level management. Changing the timing of peak inflows, to potentially 30 or more days earlier in the year will mean that current inflow forecasting methods are inadequate and will need to be re-examined over time.[1]

[1] This is already underway at the BC River Forecast Centre, who are running an ensemble-based forecast model for Okanagan Lake inflows in parallel with the regression-based methods.

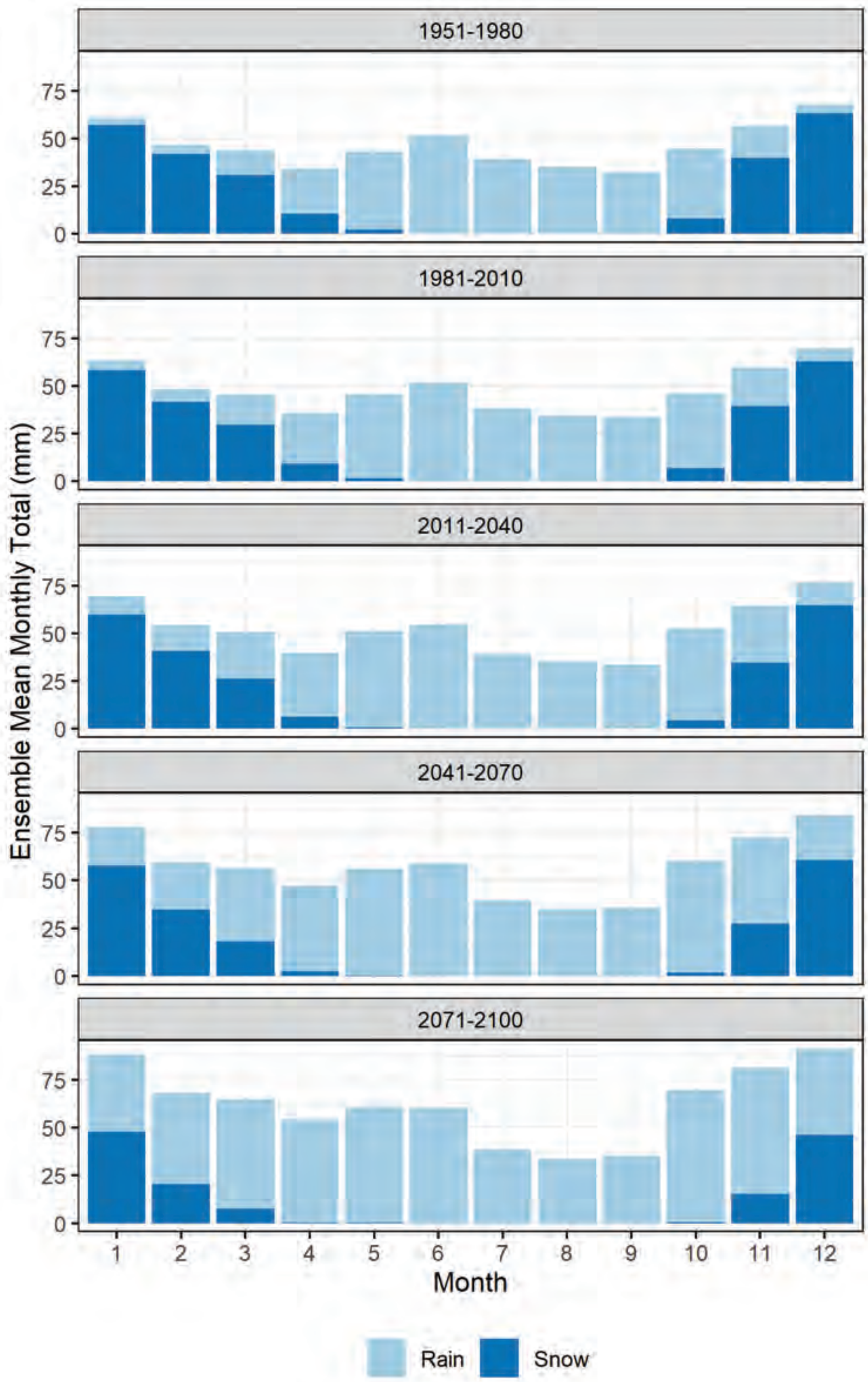


Figure 3-22 Mean monthly total precipitation by type (Snow or Rain) for the 50 ensembles.

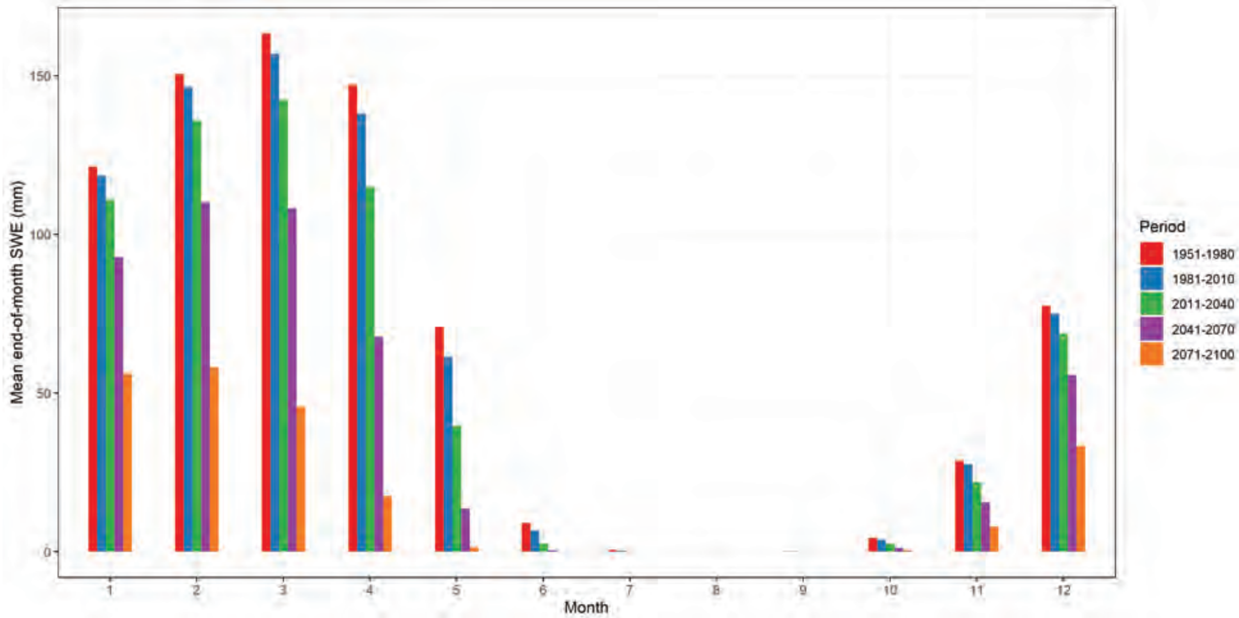


Figure 3-23 Mean end-of-the month SWE for the 50 climate ensembles averaged across the ORB.

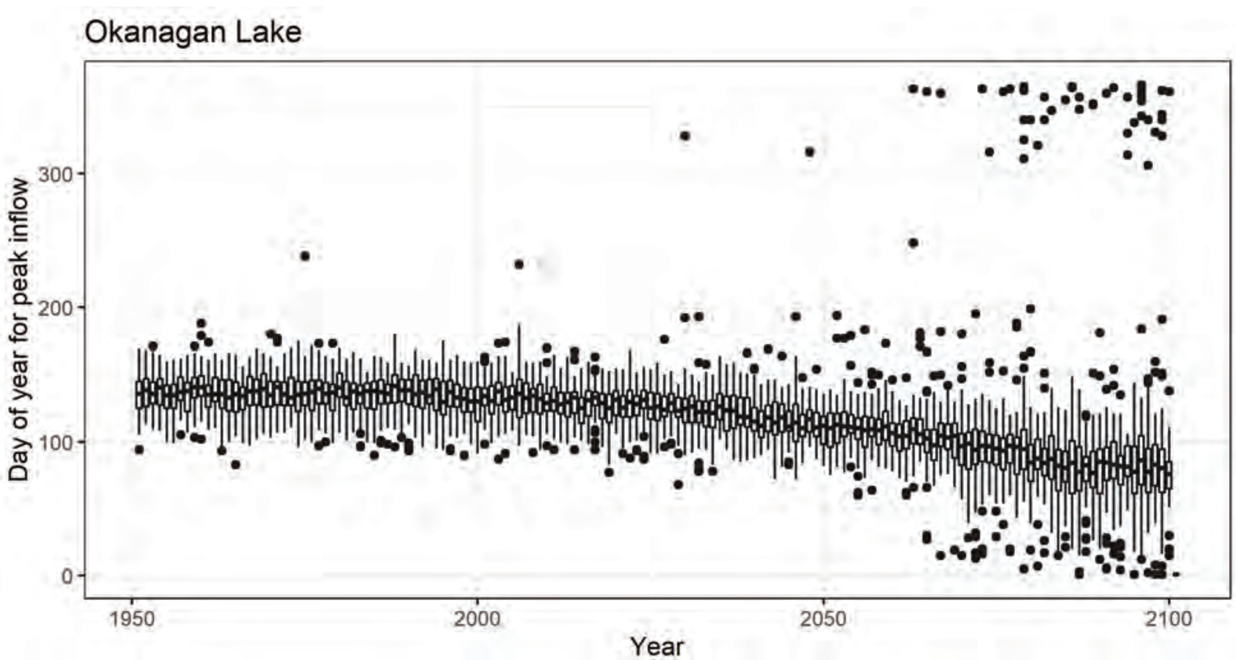


Figure 3-24 Timing of peak inflow date (shown as the day of the year) for ensemble simulation of Okanagan Lake. Each year is represented by a boxplot of the 50 ensemble members where the center line of the box is the ensemble median, the ends of the box represent the 25th and 75th percentiles, and outliers (outside 1.5X the 25-75% range) are shown as points.

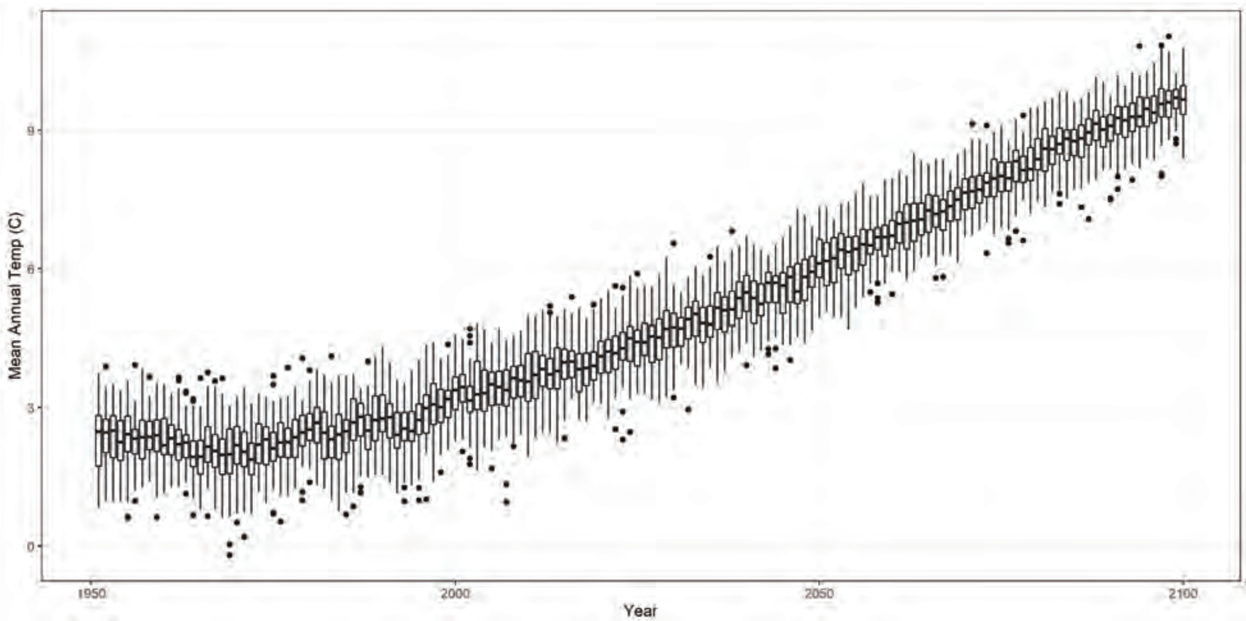


Figure 3-25 Mean Annual temperature at snow stations for 50 climate ensembles.

Ensemble results for mainstem reservoirs

This section shows the ensemble output for the mainstem lakes (aside from Osoyoos) and for WSC gauge 08NM085 – Okanagan River near Oliver. All 50 ensembles are plotted on top of one another for each of the lakes. When available, the 2017 maximum daily level is shown in orange. All figures illustrate that the 2017 event appears to be a quite rare and extreme event in the historical record (i.e. before the present day). However, in all cases, the event of 2017 becomes continually more common into the future through the end of the century. As these larger events become more common and the hydrology of the basin changes, it is likely that infrastructure upgrades will become necessary. Because of this substantial uncertainty in infrastructure and regulatory guidelines changes that will be necessary by the end of the century, we recommend the use of predictions for mid-century (defined here as 2041-2070) rather than the end of the 21st century. As the Okanagan appears to be in a period of hydrologic change, it cannot be known specifically how fast (or slow) these changes may occur. We expect this analysis will need to be revisited in approximately 10-15 years as the infrastructure and climate of the Okanagan continues to change.

For the lakes with regulatory rules that dictate the levels (Kalamalka/Wood: Figure 3-26 and Figure 3-27, Okanagan: Figure 3-28 and Figure 3-29), the change between the current regulation scenario and the future regulation scenario is evident. Without regulations changes, model results show extremely high levels may be possible in the future. Potential future regulations changes have thus far only been estimated in cooperation with the current operator, Shaun Reimer. For true changes to future regulations, a much larger group of stakeholders will need to be involved. These model results can only illustrate the potential impact of such changes on future levels. For plots showing potential regulation changes, lake levels prior to the present day (2020) are also decreased, as these changes were applied to the full 1950-2100 series' but are not relevant to the present study.

The remainder of the mainstem lakes are shown in Figure 3-32, Figure 3-30, and Figure 3-31. Note that for Skaha and Vaseux Lake, results are from the gates open scenario. For Ellison Lake, there is no impact of scenario changes, as it is at the headwater of the Okanagan Mainstem (as defined in this project).

Figure 3-33 shows the daily discharge at Okanagan River at Oliver, illustrating an increase in extreme peak daily discharges at Oliver.

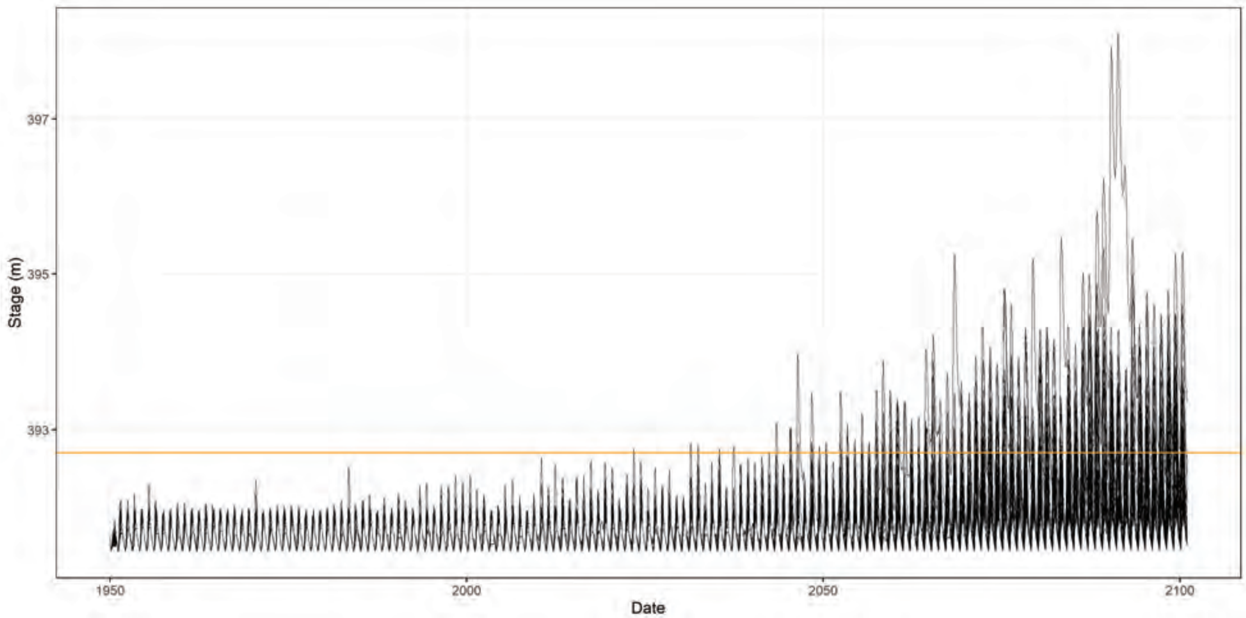


Figure 3-26 Lake levels at Kalamalka and Wood Lake from 1950 to 2100 for the present regulation scenario; orange line indicates 2017 maximum lake level.

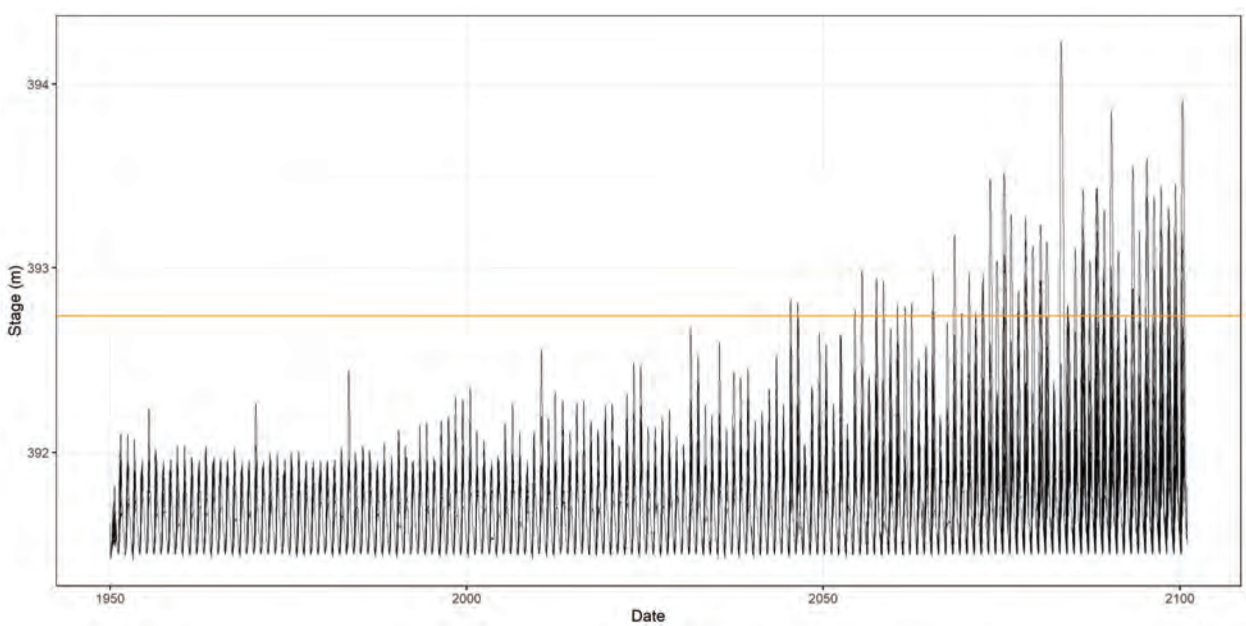


Figure 3-27 Lake levels at Kalamalka and Wood Lake from 1950 to 2100 for future regulation scenario; orange line indicates 2017 maximum lake level.

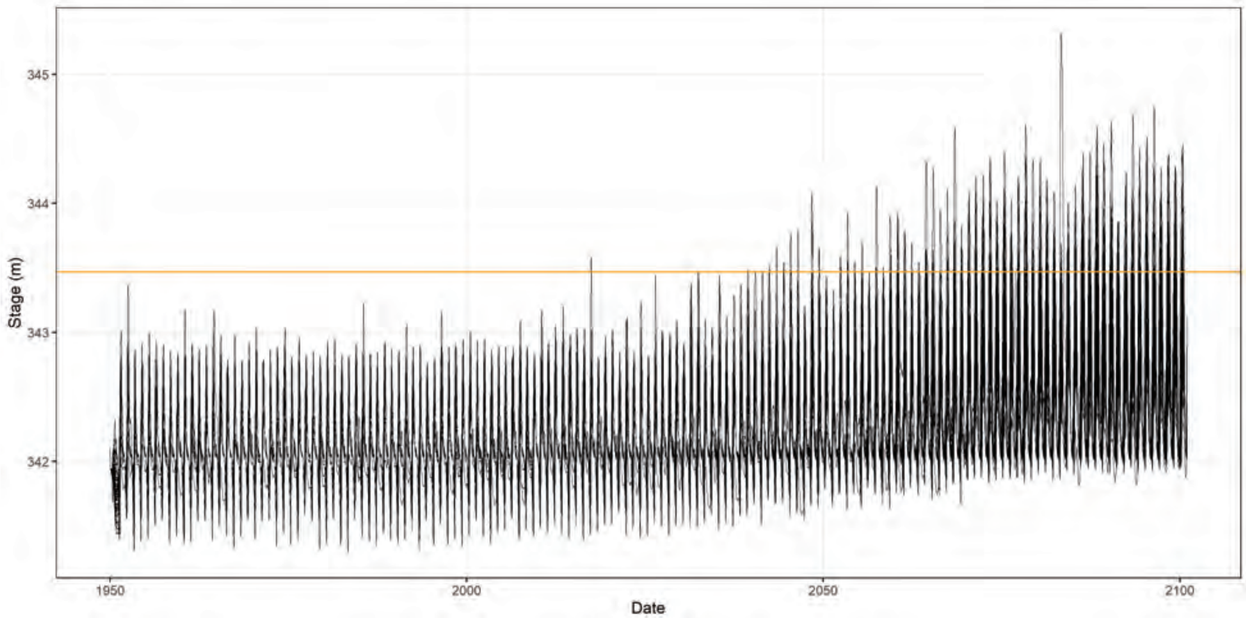


Figure 3-28 Lake levels at Okanagan Lake from 1950 to 2100 for the present regulation scenario; orange line indicates 2017 maximum lake level.

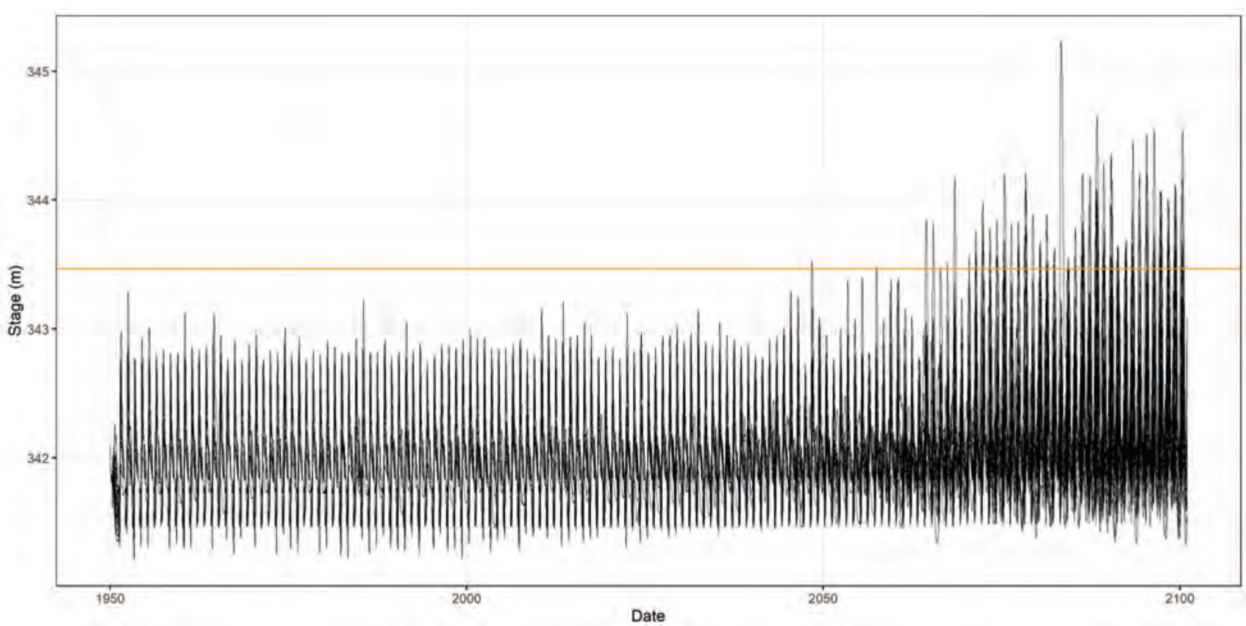


Figure 3-29 Lake levels at Okanagan Lake for the future regulation scenario from 1950 to 2100; orange line indicates 2017 maximum lake level.

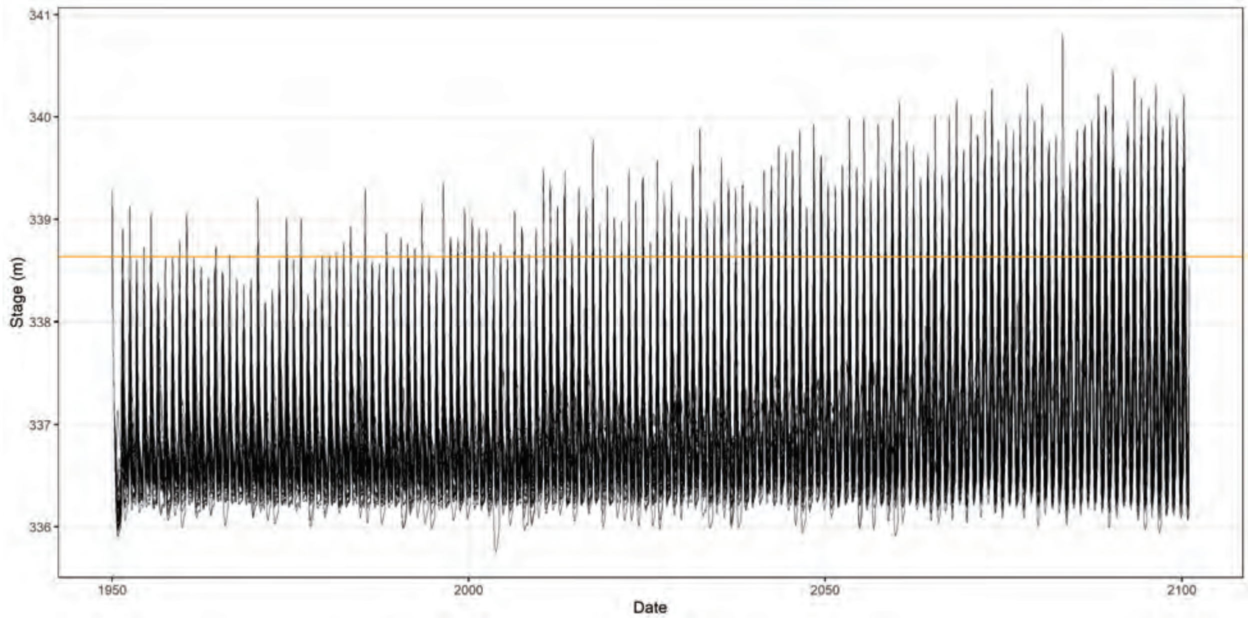


Figure 3-30 Lake levels at Skaha Lake from 1950 to 2100 for the gates open scenario; orange line indicates 2017 maximum lake level.

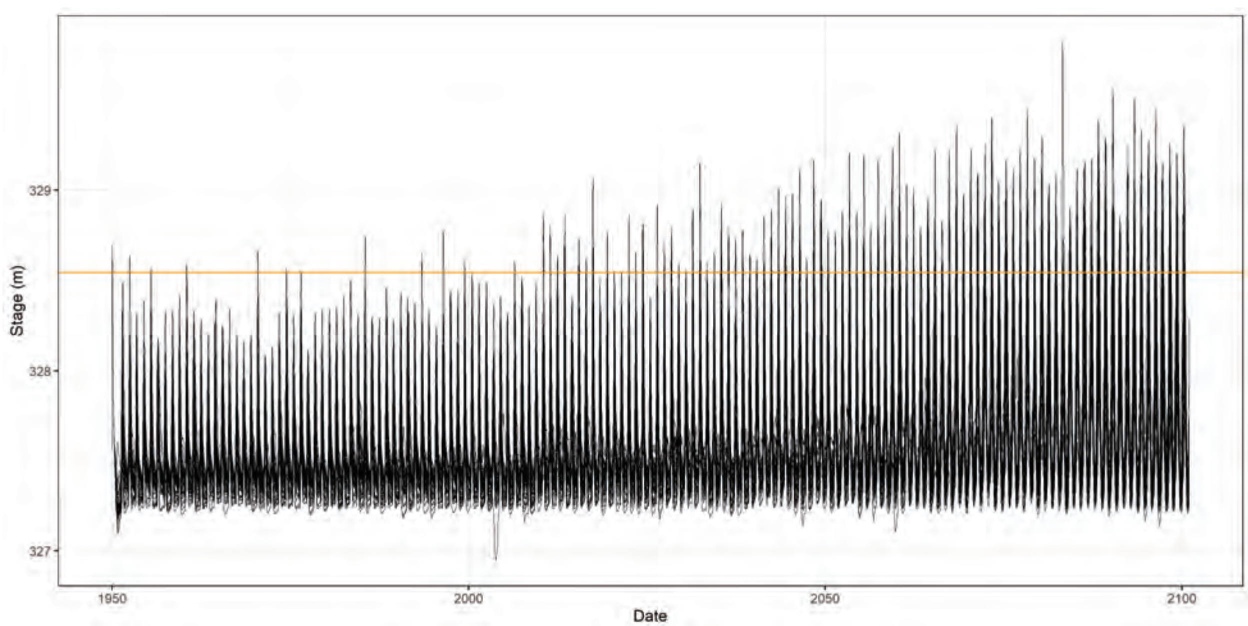


Figure 3-31 Lake levels at Vaseux Lake from 1950 to 2100 for the gates open scenario; orange line indicates 2017 maximum lake level.

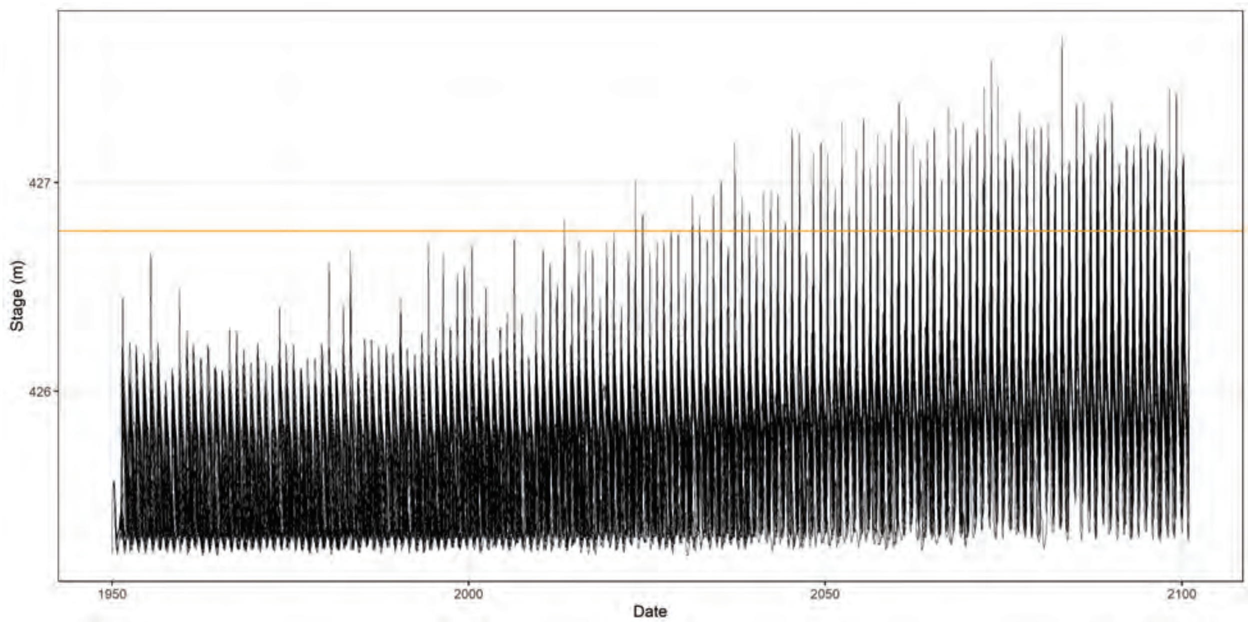


Figure 3-32 Lake levels at Ellison Lake from 1950 to 2100; orange line indicates 2017 maximum lake level (estimated from Lidar).

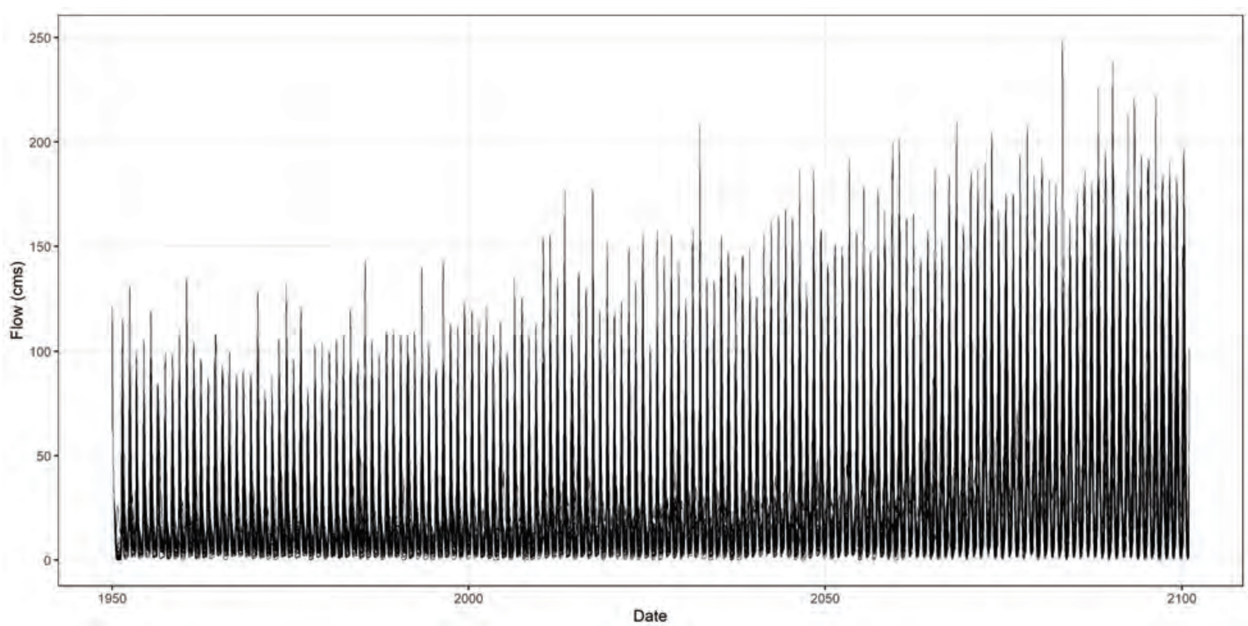


Figure 3-33 Daily discharge at Okanagan River at Oliver from 1950 to 2100 for Gates Open Scenario.

3.4 Frequency Analysis

In a regulated system such as the ORB, most assumptions of standard flood frequency analysis, where an extreme value distribution is fitted to a relatively small sample of data, are violated; hence a standard frequency analysis method is inappropriate. The use of ensemble simulation, and the resulting 7500 years of data output has advantages for a heavily regulated system such as the ORB. Because of the large number of years simulated, a distribution fit is not required in order to extrapolate to low probability events that are necessary for determining design levels and flows.

Instead, a direct calculation of design levels and flows is possible using an empirical frequency analysis (sometimes referred to as a plotting position calculation). Empirical frequency analysis is calculated, for each of i events in a record, as follows:

$$1 - AEP = \frac{i - a}{n + 1 - 2a}$$

where AEP is the annual exceedance probability, i is the rank (ascending) of a data observation, n is the total number of observations, and a is an adjustment factor. The AEP is converted to an average recurrence interval (ARI, years) as:

$$ARI = \frac{1}{AEP}$$

A range of values for the factor (a) have been suggested in the literature. In this analysis, a=0, known as the Weibull plotting position formula was used. The Weibull formula provides unbiased exceedance probability for all distributions (Asquith, 2011). The Weibull formula produces the most conservative empirical results and hence was deemed most appropriate in this case.

The results presented in section 3.3.5 were used to empirically calculate the ARI for mainstem lake levels and flows on the Okanagan river. Since the 50 climate ensembles represent an equally likely potential climate the combined 7500-year snapshot of basin behaviour could be used to directly determine empirical probabilities. However, non-stationarity due to changing climate invalidates using the entire period from 1950 – 2100 to calculate ARIs. Therefore, the record was broken into shorter, 30-year periods (a commonly used length of time for representing climate normals) with results from all 50 ensembles lumped together as a single 1500 year series; an approach for climate change analysis of extreme values accepted in scientific literature (Curry et al., 2019; Martel et al., 2020) and recommended by climatologists (Alex Cannon, ECCC, pers. communication 2018). These periods were applied to both modelling scenarios (Standard Regulation (with Modifications for Mid- and End of Century Simulations) and Open Gates Scenario) and include:

- Historical: 1950 – 2019
- Present: 2006 – 2035 (representing the present day +/- 15 years)
- Mid-Century: 2041 – 2070
- End of Century: 2071 - 2100

An example empirical analysis output for the present-day Okanagan Lake levels is shown in Figure 3-34. The figure illustrates that the large sample of annual maxima (50*30 = 1500 years) means that empirical flood quantiles can be calculated up to very high ARIs. Additionally, the figure illustrates that fitting a standard distribution to the heavily regulated data would be inappropriate. In most cases, the lake level reaches an annual maximum in a very short range of lake levels (342.5-343 m); and hence a large flat spot on the ARI curve occurs. This illustrates that, for the majority of years, target lake levels are set and achieved. This situation cannot be extrapolated out to high levels or down to drought levels[1].

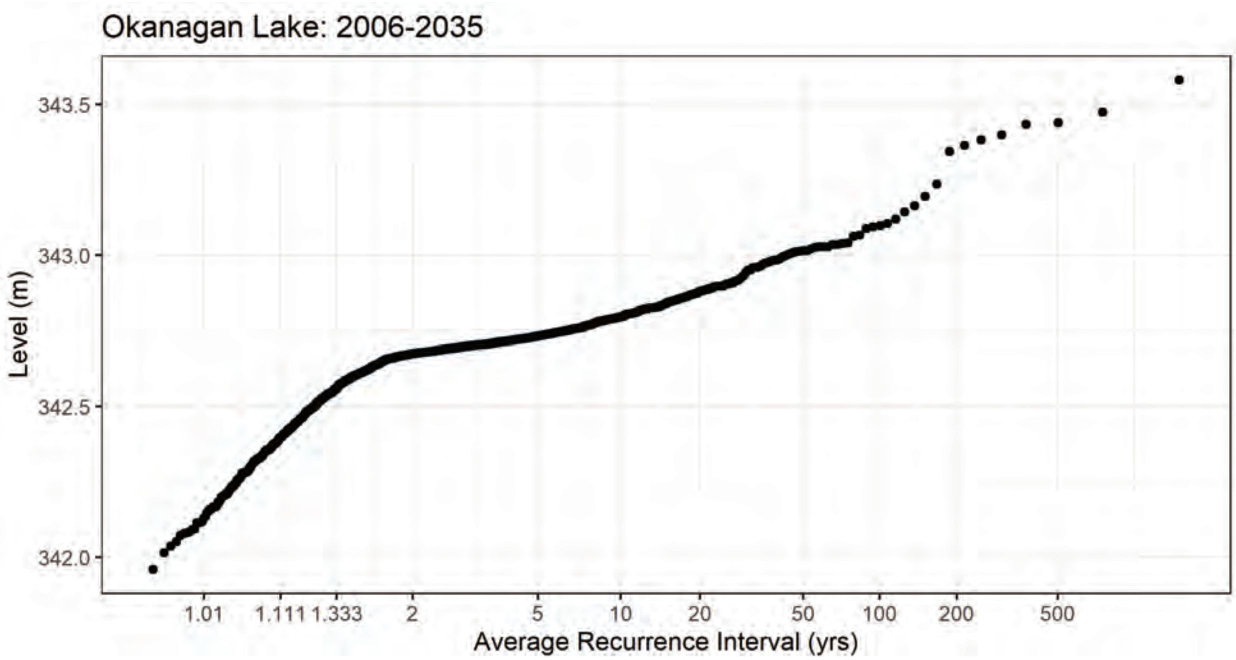


Figure 3-34 Empirical flood frequency analysis example for the 1500 years of simulation from 2006:2035 using the Weibull formula.

Design criteria are typically based on instantaneous values as opposed to maximum daily values. To convert the output from the daily timestep Raven model to instantaneous values, corrections were calculated. Offset corrections were determined at all WSC stage stations and correction multipliers were calculated at all WSC discharge stations on the Okanagan River. These values were calculated by comparing ranked max daily values verses ranked instantaneous peak values.

Table 3-16 through Table 3-22 show the instantaneous peak lake levels for the mainstem lakes for each period and model scenario. Table 3-23 through Table 3-29 show the instantaneous peak discharges on Okanagan River at various locations for each period and model scenario. The recommended design values are discussed in section 3.5.

[1] Note that the model was not developed for or tested on drought levels.

Table 3-16 Instantaneous peak lake levels for the Historical period (1950 - 2019) using the standard regulation scenario.

ARI (years)	Instantaneous Peak Lake Levels (m)					
	Ellison[1]	Kalamalka/Wood[2]	Okanagan[3]	Skaha[4]	Vaseux[5]	Osoyoos[6]
2	425.83	391.97	342.67	N/A	328.33	N/A
5	426.05	391.97	342.73	N/A	328.35	N/A
10	426.12	391.98	342.77	N/A	328.42	N/A
20	426.20	391.99	342.82	N/A	328.51	N/A
50	426.32	392.12	342.90	N/A	328.59	N/A
100	426.50	392.21	342.95	N/A	328.65	N/A
200	426.61	392.32	343.04	N/A	328.70	N/A
300	426.68	392.37	343.08	N/A	328.74	N/A
400	426.69	392.41	343.13	N/A	328.77	N/A
500	426.70	392.42	343.18	N/A	328.79	N/A

1. 0.015 m offset applied; used same offset as Kalamalka as no data available for Ellison Lake.
2. 0.015 m offset applied.
3. 0.012 m offset applied.
4. 0.001 m offset applied.
5. 0.01 m offset applied.
6. 0.008 m offset applied; data includes backwater from Similkameen.

Table 3-17 Instantaneous peak lake levels for the Present period (2006 - 2035) using the standard regulation scenario.

ARI (years)	Instantaneous Peak Lake Levels (m)[1]					
	Ellison	Kalamalka/Wood	Okanagan	Skaha	Vaseux	Osoyoos
2	426.03	391.97	342.69	N/A	N/A	N/A
5	426.18	391.98	342.74	N/A	N/A	N/A
10	426.29	392.03	342.81	N/A	N/A	N/A
20	426.51	392.16	342.89	N/A	N/A	N/A
50	426.69	392.35	343.03	N/A	N/A	N/A
100	426.77	392.52	343.11	N/A	N/A	N/A
200	426.84	392.61	343.37	N/A	N/A	N/A
300	426.86	392.66	343.41	N/A	N/A	N/A
400	426.95	392.77	343.45	N/A	N/A	N/A
500	426.95	392.77	343.45	N/A	N/A	N/A

1. Same offsets applied as in Table 3-16.

Table 3-18 Instantaneous peak lake levels for the Present period (2006 – 2035) using the gates open scenario.

ARI (years)	Instantaneous Peak Lake Levels (m)[1,2]					
	Ellison	Kalamalka/Wood	Okanagan	Skaha	Vaseux	Osoyoos
2	N/A	N/A	N/A	337.91	327.95	278.2
5	N/A	N/A	N/A	338.38	328.20	278.54
10	N/A	N/A	N/A	338.65	328.35	278.91
20	N/A	N/A	N/A	338.89	328.49	279.24
50	N/A	N/A	N/A	339.13	328.64	279.55
100	N/A	N/A	N/A	339.36	328.78	279.9
200	N/A	N/A	N/A	339.50	328.88	280.33
300	N/A	N/A	N/A	339.54	328.91	280.52
400	N/A	N/A	N/A	339.59	328.93	280.56
500	N/A	N/A	N/A	339.60	328.94	280.59

1. Same offsets applied as in Table 3-16.
2. Gates Open Scenario only relevant for lakes downstream of Okanagan Lake.

Table 3-19 Instantaneous peak lake levels for the Mid-Century period (2041 - 2070) for the modified regulation scenario.

ARI (years)	Instantaneous Peak Lake Levels (m)[1]					
	Ellison	Kalamalka/Wood	Okanagan	Skaha	Vaseux	Osoyoos
2	426.25	391.97	342.53	N/A	N/A	N/A
5	426.67	391.97	342.71	N/A	N/A	N/A
10	426.84	392.13	342.75	N/A	N/A	N/A
20	426.98	392.30	342.89	N/A	N/A	N/A
50	427.12	392.56	343.10	N/A	N/A	N/A
100	427.22	392.77	343.36	N/A	N/A	N/A
200	427.28	392.84	343.48	N/A	N/A	N/A
300	427.31	392.95	343.55	N/A	N/A	N/A
400	427.32	392.98	343.64	N/A	N/A	N/A
500	427.33	392.99	343.84	N/A	N/A	N/A

1. Same offsets applied as in Table 3-16.

Table 3-20 Instantaneous peak lake levels for the Mid-Century period (2041 - 2070) for the gates open scenario.

ARI (years)	Instantaneous Peak Lake Levels (m)[1,2]					
	Ellison	Kalamalka/Wood	Okanagan	Skaha	Vaseux	Osoyoos
2	N/A	N/A	N/A	338.34	328.18	278.3
5	N/A	N/A	N/A	338.84	328.46	278.87
10	N/A	N/A	N/A	339.15	328.64	279.24
20	N/A	N/A	N/A	339.37	328.79	279.52
50	N/A	N/A	N/A	339.62	328.95	279.85
100	N/A	N/A	N/A	339.72	329.03	280.07
200	N/A	N/A	N/A	339.98	329.21	280.36
300	N/A	N/A	N/A	340.01	329.23	280.49
400	N/A	N/A	N/A	340.02	329.24	280.63
500	N/A	N/A	N/A	340.02	329.25	280.68

1. Same offsets applied as in Table 3-16.
2. Gates Open Scenario only relevant for lakes downstream of Okanagan Lake.

Table 3-21 Instantaneous peak lake levels for the End of Century period (2071 - 2100) for the modified regulation scenario.

ARI (years)	Instantaneous Peak Lake Levels (m)[1,2]					
	Ellison	Kalamalka/Wood	Okanagan	Skaha	Vaseux	Osoyoos
2	426.60	391.97	342.60	N/A	N/A	N/A
5	426.86	392.11	343.04	N/A	N/A	N/A
10	427.02	392.42	343.47	N/A	N/A	N/A
20	427.13	392.75	343.65	N/A	N/A	N/A
50	427.22	393.13	343.98	N/A	N/A	N/A
100	427.30	393.34	344.19	N/A	N/A	N/A
200	427.40	393.48	344.37	N/A	N/A	N/A
300	427.47	393.56	344.51	N/A	N/A	N/A
400	427.48	393.66	344.56	N/A	N/A	N/A
500	427.48	393.87	344.56	N/A	N/A	N/A

1. Same offsets applied as in Table 3-16.

Table 3-22 Instantaneous peak lake levels for the End of Century period (2071 - 2100) for the gates open scenario.

ARI (years)	Instantaneous Peak Lake Levels (m)[1,2]					
	Ellison	Kalamalka/Wood	Okanagan	Skaha	Vaseux	Osoyoos
2	N/A	N/A	N/A	338.66	328.35	278.39
5	N/A	N/A	N/A	339.17	328.66	279.02
10	N/A	N/A	N/A	339.47	328.87	279.36
20	N/A	N/A	N/A	339.73	329.04	279.73
50	N/A	N/A	N/A	339.95	329.18	280.05
100	N/A	N/A	N/A	340.09	329.29	280.31
200	N/A	N/A	N/A	340.22	329.39	280.64
300	N/A	N/A	N/A	340.32	329.46	280.75
400	N/A	N/A	N/A	340.34	329.47	280.88
500	N/A	N/A	N/A	340.38	329.51	280.99

1. Same offsets applied as in Table 3-16.
2. Gates Open Scenario only relevant for lakes downstream of Okanagan Lake.

Table 3-23 Instantaneous Peak Discharges on Okanagan River for the Historic Period (1950 - 2019) for the Standard Regulation Scenario.

ARI (years)	Instantaneous Peak Discharge (m^3/s) on Okanagan River						
	08NM050 - Outlet from Okanagan Lake[1]	Into Skaha Lake[1]	08NM002- Outlet from Skaha Lake[2]	Into Vaseux Lake[2]	08NM247 - Outlet from Vaseux Lake[2]	08NM085 - Near Oliver[2]	Into Osoyoos Lake[2]
2	82.7	89.2	88.4	90.4	90.5	99.2	99.1
5	82.7	94.4	88.4	92.8	92.8	108.6	108.6
10	82.7	97.9	95.2	98.6	98.5	117.5	117.5
20	82.7	100.9	100.8	105.9	105.9	127.2	127.2
50	82.7	105.2	107.1	114.0	113.5	141.4	141.3
100	82.7	108.0	110.7	118.1	118.0	149.9	149.8
200	82.7	111.7	115.4	123.8	123.1	157.6	157.5
300	82.7	112.6	117.0	126.1	126.6	160.4	160.3
400	82.7	114.6	119.8	129.1	129.0	168.3	168.3
500	82.7	116.2	121.5	131.7	131.2	172.0	171.7

1. Multiplier of 1.06 applied.
2. Multiplier of 1.04.

Table 3-24 Instantaneous Peak Discharges on Okanagan River for the Present Period (2006 - 2035) for the Standard Regulation Scenario

ARI (years)	Instantaneous Peak Discharge (m^3/s) on Okanagan River[1]						
	08NM050 - Outlet from Okanagan Lake[1]	Into Skaha Lake[1]	08NM002- Outlet from Skaha Lake[2]	Into Vaseux Lake[2]	08NM247 - Outlet from Vaseux Lake[2]	08NM085 - Near Oliver[2]	Into Osoyoos Lake[2]
2	82.7	92.5	88.4	91.5	91.5	104.2	104.1
5	82.7	98.4	96.8	100.5	100.5	118.7	118.7
10	82.7	102.3	102.8	108.6	108.3	132.4	132.3
20	82.7	106.2	107.5	114.5	114.3	141.8	141.7
50	82.7	110.8	113.6	122.4	122.7	155.8	155.7
100	82.7	114.8	119.6	128.6	128.1	165.5	165.3
200	82.7	116.8	122.0	132.9	132.7	174.8	174.6
300	82.7	117.9	123.2	133.4	133.2	177.7	177.6
400	82.7	119.0	124.8	134.2	133.3	178.0	177.9
500	82.7	119.1	126.1	135.3	133.5	178.9	178.9

1. Multiplier of 1.06 applied.
2. Multiplier of 1.04.

Table 3-25 Instantaneous Peak Discharges on Okanagan River for the Present Period (2006 - 2035) for the Gates Open Scenario.

ARI (years)	Instantaneous Peak Discharge (m^3/s) on Okanagan River[1]						
	08NM050 - Outlet from Okanagan Lake[1]	Into Skaha Lake[1]	08NM002- Outlet from Skaha Lake[2]	Into Vaseux Lake[2]	08NM247 - Outlet from Vaseux Lake[2]	08NM085 - Near Oliver[2]	Into Osoyoos Lake[2]
2	50.5	56.9	54.8	56.4	56.3	65.1	65.0
5	70.1	78.8	76.6	78.6	78.5	90.4	90.4
10	82.0	92.3	90.3	92.4	92.3	105.2	105.2
20	94.1	105.6	103.0	105.4	105.4	119.2	119.2
50	107.0	118.9	116.7	119.7	119.7	140.0	139.8
100	116.9	130.2	130.2	132.5	132.4	153.7	153.7
200	126.4	141.5	138.1	141.4	141.4	161.8	161.7
300	130.0	146.3	140.9	143.8	143.7	164.0	164.0
400	131.3	147.1	143.4	146.2	146.1	168.3	168.2
500	133.3	147.8	144.5	146.9	146.8	183.7	183.6

1. Multiplier of 1.06 applied.
2. Multiplier of 1.04.

Table 3-26 Instantaneous Peak Discharges on Okanagan River for the Mid-century Period (2041 – 2070) for the Standard Regulation Scenario with operations modifications.

ARI (years)	Instantaneous Peak Discharge (m^3/s) on Okanagan River[1]						
	08NM050 - Outlet from Okanagan Lake[1]	Into Skaha Lake[1]	08NM002- Outlet from Skaha Lake[2]	Into Vaseux Lake[2]	08NM247 - Outlet from Vaseux Lake[2]	08NM085 - Near Oliver[2]	Into Osoyoos Lake[2]
2	82.7	97.1	95.4	99.1	99.0	116.0	115.9
5	82.7	103.2	104.2	110.2	109.9	134.6	134.6
10	82.7	106.5	108.2	115.6	115.6	144.3	144.3
20	82.7	109.5	112.1	120.9	120.1	151.8	151.8
50	82.7	113.1	116.6	125.4	125.3	161.9	161.4
100	82.7	118.1	119.5	129.3	128.7	167.1	166.9
200	105.4	119.9	124.3	134.8	134.5	178.7	178.6
300	106.0	123.3	126.8	138.8	136.9	182.2	182.1
400	106.0	125.2	130.8	140.5	141.4	183.3	183.1
500	106.0	128.8	133.9	145.0	145.5	184.8	184.6

1. Multiplier of 1.06 applied.
2. Multiplier of 1.04.

Table 3-27 Instantaneous Peak Discharges on Okanagan River for the Mid-century Period (2041 – 2070) for the Gates Open Scenario.

ARI (years)	Instantaneous Peak Discharge (m^3/s) on Okanagan River[1]						
	08NM050 - Outlet from Okanagan Lake[1]	Into Skaha Lake[1]	08NM002- Outlet from Skaha Lake[2]	Into Vaseux Lake[2]	08NM247 - Outlet from Vaseux Lake[2]	08NM085 - Near Oliver[2]	Into Osoyoos Lake[2]
2	68.3	77.3	74.8	76.7	76.6	88.1	88.1
5	93.4	103.6	100.7	103.1	103.0	117.6	117.6
10	108.8	121.1	117.5	119.6	119.6	135.7	135.6
20	118.6	133.1	130.5	133.0	132.9	151.0	150.9
50	132.9	147.1	145.3	147.7	147.6	167.7	167.7
100	140.1	155.4	151.8	154.6	154.5	174.2	173.9
200	153.0	171.7	168.0	171.2	171.1	193.5	193.4
300	156.0	173.1	170.1	173.2	173.2	195.0	194.9
400	158.3	174.0	170.5	174.0	174.0	201.1	201.1
500	158.9	174.5	170.8	174.3	174.4	207.6	207.5

1. Multiplier of 1.06 applied.
2. Multiplier of 1.04.

Table 3-28 Instantaneous Peak Discharges on Okanagan River for the Distant Period (2071 – 2100) for the Standard Regulation Scenario with operations modifications.

ARI (years)	Instantaneous Peak Discharge (m^3/s) on Okanagan River[1]						
	08NM050 - Outlet from Okanagan Lake[1]	Into Skaha Lake[1]	08NM002- Outlet from Skaha Lake[2]	Into Vaseux Lake[2]	08NM247 - Outlet from Vaseux Lake[2]	08NM085 - Near Oliver[2]	Into Osoyoos Lake[2]
2	82.7	97.2	96.8	100.4	100.1	118.0	117.8
5	82.7	103.6	106.2	112.1	112.0	136.7	136.7
10	82.7	114.9	117.7	122.0	121.9	148.3	148.1
20	106.0	122.1	124.5	130.4	130.0	159.9	159.8
50	106.0	128.9	132.9	138.7	137.7	172.2	172.2
100	106.0	133.2	142.6	148.9	146.4	182.5	182.3
200	106.0	139.3	147.2	154.4	152.6	192.6	192.3
300	106.0	142.8	153.1	160.9	156.7	201.9	201.4
400	106.0	143.7	155.8	165.5	164.3	214.1	214.2
500	106.0	145.3	157.8	169.0	167.4	223.6	222.9

1. Multiplier of 1.06 applied.
2. Multiplier of 1.04.

Table 3-29 **Instantaneous Peak Discharges on Okanagan River for the End of Century Period (2071 – 2100) for the Gates Open Scenario.**

ARI (years)	Instantaneous Peak Discharge (m^3/s) on Okanagan River[1]						
	08NM050 - Outlet from Okanagan Lake[1]	Into Skaha Lake[1]	08NM002- Outlet from Skaha Lake[2]	Into Vaseux Lake[2]	08NM247 - Outlet from Vaseux Lake[2]	08NM085 - Near Oliver[2]	Into Osoyoos Lake[2]
2	83.4	93.1	90.8	92.8	92.7	105.1	105.1
5	109.7	120.9	119.0	121.3	121.3	138.4	138.4
10	124.9	139.2	136.7	139.7	139.7	155.9	155.9
20	139.6	155.4	152.0	155.5	155.5	174.9	174.9
50	152.7	168.3	166.1	168.8	168.9	191.7	191.7
100	160.5	177.5	175.4	178.3	178.4	200.9	201.0
200	169.4	185.5	183.5	187.4	187.7	216.5	216.5
300	172.9	193.2	190.2	194.2	194.3	229.8	229.8
400	174.7	194.8	191.5	195.3	195.5	231.2	231.1
500	176.0	195.9	194.3	198.9	199.1	234.7	234.5

1. Multiplier of 1.06 applied.
2. Multiplier of 1.04.

3.5 Recommended Design Levels and Flows

The recommended design levels and flows for the ORB are presented in this section. The results summarized in section 3.4 were presented to OBWB, and the results of this discussion are presented here. The Gates Open Scenario under normal operation, releases from Okanagan Lake would never exceed the maximum allowable outflow of 78 m^3/s. In this scenario, frequency curves would plateau; the 10-year ARI had the same value as the 200-year ARI (see Table 3-26, 08NM050). The gates open scenario was adopted for all design criteria downstream of Okanagan Lake as a safety factor to account for the potential for upstream reservoirs being unable to operate properly and to account for this plateauing of maximum outflows. Table 3-30 summarizes the recommended current design levels for the mainstem lakes and Table 3-31 compares the 2017 flood levels to the previous and recommended design levels and provides estimated ARIs. The 200-year ARI has been selected as the design level for all lakes except Okanagan and Kalamalka. The 2017 event, as the event of record, has been selected as the design level for Okanagan and Kalamalka. The modelled lake levels on Osoyoos Lake, determined using the gates open scenario, exceed both the 2017 and 1894 observed levels; hence the 200-year model ARI is recommended for Osoyoos Lake

Table 3-30 Design instantaneous peak lake levels for mainstem lakes for Present Period (2006 - 2035).

ARI (years)	Instantaneous Peak Lake Level (m)[1,2]					
	Ellison[3]	Kalamalka/Wood[3]	Okanagan[3]	Skaha[4]	Vaseux[4]	Osoyoos[5]
100	426.77	392.52	343.11	339.36	328.78	279.9
200	**426.84**	392.61	343.37	**339.50**	**328.88**	**280.33**
300	426.86	392.66	343.41	339.54	328.91	280.52
400	426.95	392.77	343.45	339.59	328.93	280.56
500	426.95	392.77	343.45	339.60	328.94	280.59
2017 Event	426.6[6]	**392.80**	**343.48**	338.36	328.29	278.98
1894 Event	n/a	n/a	n/a	n/a	n/a	280.12

1. Freeboard will be applied to these levels in Chapter 6.
2. Recommended design level is **bolded** for each lake.
3. Values from Standard Regulation Scenario.
4. Values from Gates Open Scenario.
5. Values from Similkameen relationship.
6. Estimated from Lidar data.

Table 3-31 2017 maximum instantaneous lake levels compared to previous and current design levels.

Lake	Previous Design Level[1]	Approximate ARI (year) in current results	
		2017 Event	Previous Design Level
Ellison	n/a	50	n/a
Kalamalka/Wood	392.49[2]	~ 500	100
Okanagan	343.27[2]	~ 500	200
Skaha	338.83[3]	5	20
Vaseux	329.2[4]	10	> 500
Osoyoos	280.93[4]	~ 10	~500

1. Converted to CGVD2013.
2. Provided in (AE, 2017b).
3. Provided in previous flood level report (BC Environment, 1991).
4. Estimated from previous floodplain mapping (Ministry of Environment, Lands and Parks Water Management Division, 1992).

The design discharges are presented in Table 3-32, note that all of these are from the Gates Open model scenario. The 2017 instantaneous peak at the Oliver gauge (08MN085) was 106 m^3/s, this has an approximate ARI of approximately 10 years.

Table 3-32 Design instantaneous peak river discharges levels for Okanagan River for the Present Period (2006 - 2035).

ARI (years)	Instantaneous Peak Discharge (m^3/s) on Okanagan River						
	Outflow from Okanagan Dam	Inlet to Skaha Lake	Outflow from Skaha Lake	Inlet to Vaseux Lake	Outflow from Vaseux Lake	Near Oliver	Inlet to Osoyoos Lake
100	116.9	130.2	130.2	132.5	132.4	153.7	153.7
200	**126.4**	**141.5**	**138.1**	**141.4**	**141.4**	**161.8**	**161.7**
300	130.0	146.3	140.9	143.8	143.7	164.0	164.0
400	131.3	147.1	143.4	146.2	146.1	168.3	168.2
500	133.3	147.8	144.5	146.9	146.8	183.7	183.6
2017 Event	n/a	n/a	90	n/a	n/a	106	n/a

1. Recommended design level is **bolded** for each river reach.

The projected Mid-Century design levels, which incorporate climate change considerations, are summarized in Table 3-33. For Okanagan and Kalamalka lakes, the 2017 Event in the context of mid-century flows was estimated by adding the difference between the 500-year in present day and mid-century. The projected Mid-Century design flows along the Okanagan River are presented in Table 3-34.

Table 3-33 Projected design instantaneous peak lake levels for mainstem lakes for the Mid-Century Period (2041 - 2070).

ARI (years)	Instantaneous Peak Lake Level (m)[1,2]					
	Ellison[3]	Kalamalka/Wood[3]	Okanagan[3]	Skaha[4]	Vaseux[4]	Osoyoos[5]
100	427.22	392.77	343.36	339.72	329.03	280.07
200	**427.28**	392.84	343.48	**339.98**	**329.21**	**280.36**
300	427.31	392.95	343.55	340.01	329.23	280.49
400	427.32	392.98	343.64	340.02	329.24	280.63
500	427.33	392.99	343.84	340.02	329.25	280.68
2017 event in mid-century	n/a	**393.02**	**343.86**	n/a	n/a	n/a

1. Freeboard will be applied to these levels in Chapter 6.
2. Recommended projected design level is **bolded** for each lake.
3. Values from Standard Regulation Scenario with operations modifications.
4. Values from Gates Open Scenario.
5. Values from Similkameen relationship.

Table 3-34 Design instantaneous peak river discharges levels for Okanagan River for the Mid-Century Period (2041 - 2070).

ARI (years)	Instantaneous Peak Discharge (m^3/s) on Okanagan River						
	Outflow from Okanagan Dam	Inlet to Skaha Lake	Outflow from Skaha Lake	Inlet to Vaseux Lake	Outflow from Vaseux Lake	Near Oliver	Inlet to Osoyoos Lake
100	140.1	155.4	151.8	154.6	154.5	174.2	173.9
200	**153.0**	**171.7**	**168.0**	**171.2**	**171.1**	**193.5**	**193.4**
300	156.0	173.1	170.1	173.2	173.2	195.0	194.9
400	158.3	174.0	170.5	174.0	174.0	201.1	201.1
500	158.9	174.5	170.8	174.3	174.4	207.6	207.5

1. Recommended design level is **bolded** for each river reach.

The End of Century design levels and discharges are being included for information purposes. There is significant uncertainty in projections, and operational changes, this far into the future and the values should not be relied upon for design purposes. Table 3-35 presents the projected levels and Table 3-36 presents the projected discharges.

Table 3-35 Projected instantaneous peak lake levels for mainstem lakes for the End of Century Period (2071 - 2100); included for information purposes only.

ARI (years)	Instantaneous Peak Lake Level (m)					
	Ellison[1]	Kalamalka/Wood[1]	Okanagan[1]	Skaha[2]	Vaseux[2]	Osoyoos[3]
100	427.30	393.34	344.19	340.09	329.29	280.31
200	427.40	393.48	344.37	340.22	329.39	280.64
300	427.47	393.56	344.51	340.32	329.46	280.75
400	427.48	393.66	344.56	340.34	329.47	280.88
500	427.48	393.87	344.56	340.38	329.51	280.99

1. Values from Standard Regulation Scenario with operations modifications.
2. Values from Gates Open Scenario.
3. Values from Similkameen relationship.

Table 3-36 Design instantaneous peak river discharges levels for Okanagan River for the End of Century Period (2071 - 2100); included for information purposes only.

ARI (years)	Instantaneous Peak Discharge (m^3/s) on Okanagan River						
	Outflow from Okanagan Dam	Inlet to Skaha Lake	Outflow from Skaha Lake	Inlet to Vaseux Lake	Outflow from Vaseux Lake	Near Oliver	Inlet to Osoyoos Lake
100	160.5	177.5	175.4	178.3	178.4	200.9	201.0
200	169.4	185.5	183.5	187.4	187.7	216.5	216.5
300	172.9	193.2	190.2	194.2	194.3	229.8	229.8
400	174.7	194.8	191.5	195.3	195.5	231.2	231.1
500	176.0	195.9	194.3	198.9	199.1	234.7	234.5

3.6 Conclusions, Recommendations, and Future Work

The hydrologic model provided unique insights into the operation of the OLRS system. While not able to perfectly emulate the human controls, the following became apparent:

- Ellison Lake is primarily controlled by outflows from Swalwell Lake.
- The maximum outflow from Kalamalka Lake should not exceed 6 m^3/s or there are significant impacts at the City of Vernon (Shaun Reimer, FLNRORD, pers. communication, 2020).
- To keep the future projections realistic the operations at Okanagan Lake had to be modified. However, these modifications will have significant impacts on downstream fish habitats and will need to be agreed on by a much larger group of stakeholders. This should be considered for future operations as some mitigation work may be required.

Recommendations include:

- This chapter showed that the approximation of peak flows for the Similkameen River using results in the ORB is insufficient for all scenarios. Thus, development of a Similkameen hydrologic model and driving it with the same climate ensembles is recommended. This model can then be combined with the ORB model to assess the influence of the Similkameen-Okanogan confluence more reliably on Osoyoos Lake levels.
- This chapter notes that the ORB Raven model in its current form is insufficient for low flow modelling, as that was not the focus of this project. If low flows in the ORB becomes a goal of hydrologic modelling in the future, this model can be extended to improve suitability for low flow simulations by including withdrawals and making considerations for the impacts of groundwater interactions with the lakes.
- At present, future reservoir operations changes were only speculated in cooperation with the reservoir operator. When the time comes that the operations rules must be officially

adjusted, the Raven ORB model can be used to explore and optimize different OLRS operation schemes for current and projected design levels. In addition, the design floods from this study must be evaluated under any future proposed changes to flow and lake level regulation.

- The ensemble simulations indicated that the regression model used as the primary inflow forecasting method is likely to soon be inadequate due to changing peak timing and flood drivers (e.g. more influence of spring rain and rapid warming). The BC River Forecast Centre is addressing this issue through initial development of ensemble streamflow prediction methods. All of these methods need to be scrutinized to account for the fact that the past weather is likely no longer a representation of potential future weather as our climate changes.
- This project (in particular the attempted modelling of the 2017 event) identified data gaps in the in the ORB, particularly in weather stations at higher elevations. A lack of weather data at high elevation is a common issue in BC. Of the ECCC high elevation stations that are available in the ORB, some are still manual, seasonal stations (e.g. the Vernon, Silverstar station). Upgrading these stations to real-time stations would improve the quality of gridded weather data products produced in the future. Additionally, inclusion of high elevation observations from other providers (e.g. the Province of BC, BC Hydro) should help improve the quality of the gridded weather data.
- As noted in the limitations section of this chapter, this project did not include the potential for infrastructure malfunction. The Raven model developed here could assist in risk assessment of dam operations (e.g. blockage, malfunction); for example, the risk of a relatively small outflow event from Okanagan Lake turning into an extreme outflow event, due to a gate blockage or malfunction preventing the Okanagan Lake Dam from impounding the event's inflow volume.
- Discussions with the reservoir operator indicated that there may be insufficient outflow capacity from Kalamalka Lake to Vernon Creek to meet reservoir targets. The outflow structure from Kalamalka Lake to Vernon Creek should be evaluated to ensure that sufficient outflow can be achieved.
- We note that large releases from Swalwell Lake could cause lake levels to rise rapidly on Ellison Lake. We recommend that the reservoir operators work with the Swalwell Lake operators and that a detailed plan for operation of releases from Swalwell Lake is obtained (or developed). This will both help for planning on Ellison Lake and on Swalwell Lake itself.
- As the hydrology of the basin changes and these larger events become more common, it is likely that infrastructure upgrades will become necessary. We expect this analysis will need to be revisited in the upcoming decades as the infrastructure and climate of the Okanagan continues to change, and our picture of a future climate (e.g. end of century) becomes clearer.

Potential future work:

- The Raven ORB model could be used for improved water supply forecasting in the basin.
- The model could be used to develop formal high-water operating rules and/or emergency plans for each reservoir.
- This study did not consider the consequences of water levels overtopping dam structures. A Dam Safety review could be conducted using the Raven ORB model (with some refinements) to simulate the Probable Maximum Flood (PMF) and dam breach and inundation modelling could be completed.

CHAPTER 4 LAKESHORE FLOODPLAINS

4.1 Chapter Synopsis

The lakeshore floodplain for the Okanagan Basin is extensive with over 300 km of coverage including Okanagan, Wood-Kalamalka, Ellison, Skaha, Vaseux, and Osoyoos lakes. The extent of the lake inundation can be determined by projecting the design lake levels across the land. However, in order to determine appropriate flood construction values the effects of waves on the shoreline must also be considered. This is completed by examining wind patterns across the lakes for seasonal storm events and modelling the resulting waves that are generated for the various individual lakes. Wave effects on the shorelines such as wave runup elevations are then determined.

The wind data for the Okanagan Basin was collected from three stations: Penticton, Kelowna and Vernon airports. These stations were chosen as the airport records are longer than other anemometer records in the area and also because anemometers at airports are generally well placed and away from obstructions (buildings and trees) that create turbulence. An analysis of the available wind data was undertaken to determine the largest storms likely to occur during the extended flood season (March – August). These values were then taken and integrated into a spatially-varying synthetic wind field for the lakeshore floodplain.

The synthetic wind field was used as input to the wave models for the individual lakes. Each lake was modelled individually, and the results provide the input necessary to determine the seastate (wave heights, periods, and directions) and the extent of the wave effects (how far onshore the waves will go). Wave runup at the shoreline, as well as flood water inundation, is an important component of the overall flood construction level (FCL) necessary to identify the flood risk to structures adjacent to lake shorelines.

4.1.1 Limitations on the Lakeshore Floodplain Component of this Study

- Where climate station elevation information was missing, a standard station elevation of 10 m above ground was assumed.
- Bathymetric maps used for the lakes were often historic and possibly out of date, especially in the nearshore. To address this potential issue in the assessment of wave effects, NHC relied upon wave heights calculated in deeper water typically about 100 metres offshore of the shoreline since the interpolated bathymetry nearshore could be shallower/deeper than it is in reality.
- Wave effects will vary depending upon the specific shoreline geometry and development. However, the study project area is too large to undertake analysis of wave effects at the scale of individual properties. Instead, a single generalized shoreline slope was used for each shoreline zone designated for each lake. The generalized shoreline slope chosen was one that was among the steeper shorelines within each zone and was exposed to the wave effects from the lake. This approach generally results in a more conservative wave runup value; it is recognized that the wave runup will be overestimated for some individual properties. There is also the possibility the wave effects will be underestimated for some properties with seawall type structures due to runup being greater for vertical walls.

- It is assumed in this analysis that the future foreshore slope and beach materials will be the same as that of the existing (or present day) foreshore. Any changes to the foreshore geometry (slopes, location of structures such as seawalls, etc.) will change the wave runup and as a result the overall FCL for individual properties.
- The accuracy of the estimation of wave runup is limited by the bathymetry available for Lake Okanagan. Higher resolution bathymetry for the lake and data collection for the nearshore could improve the determination of wave effects on the shoreline and is recommended for site specific analysis.

4.2 Analysis of Observed Wind and Pressure

4.2.1 Wind Data

Hourly historical weather data was extracted from ECCC in the Okanagan Basin. Only stations with hourly data sampling intervals were considered in this analysis. Any stations with longer intervals between wind data records were not included. The station identification (ID), data interval, location, and elevation for the stations selected for the analysis are summarized in Table 4-1.

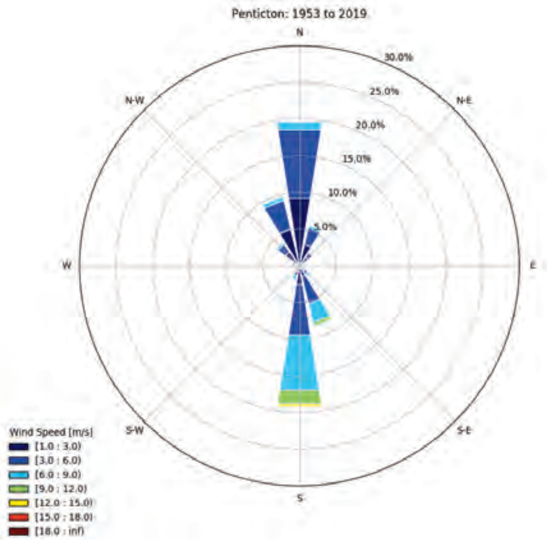
Table 4-1 Climate Canada Stations Information.

Area	Station Name	Station ID	Climate ID	Station location		Data Interval		Station Elevation (m)
				Latitude	Longitude	Start	End	
Penticton	Penticton A	1053	1126150	49°27'47.0	119°36'08.0	1953	2012	344.40
	Penticton A	50269	1126146	49°27'45.0	119°36'08.0	2012	2020	344.40
Kelowna	Kelowna A	1001	1123970	49°57'22.0	119°22'40.0	1959	2005	429.50
	Kelowna AWOS	30954	1123965	49°57'22.0	119°22'40.0	2004	2009	429.50
	Kelowna	48369	1123939	49°57'26.0	119°22'40.0	2009	2020	433.10
Vernon	Vernon CS	6837	1128581	50°13'23.9	119°11'36.8	1994	2008	482.00
	Vernon Auto	46987	1128582	50°13'23.9	119°11'36.7	2007	2020	482.00

4.2.2 Wind Rose Plots

The wind station's data for each area was combined and analyzed to generate rose plot diagrams which are shown in the following figures. The rose plots clearly show that surface level winds tend to align with the primary axis of the valleys in the region and that winds in general are light in this region.

Penticton – Primarily northerly (N) and southerly (S) winds, following the valley orientation at this location (Figure 4-1). Station located immediately south of Okanagan Lake. South southeasterly (SSE) and north northwesterly (NNW) winds are also recorded.



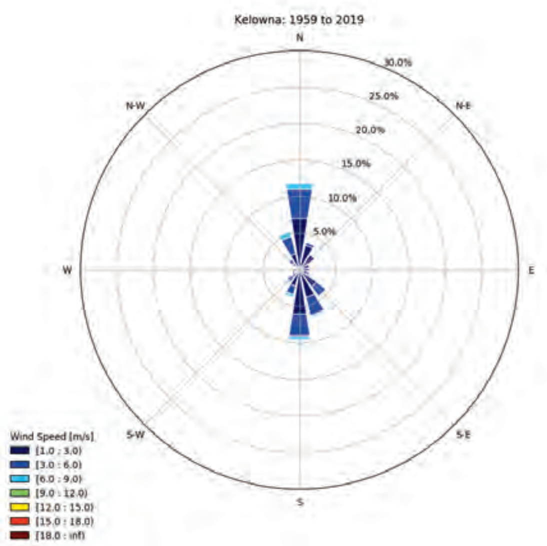
Wind Speed and Direction Frequency Distribution

	1 - 3	3 - 6	6 - 9	9 - 12	12 - 15	15 - 18	> 18	Total (%)
N	9.3	9.4	1.1	0.1	0.0	0.0	0.0	19.9
NNE	3.0	2.3	0.4	0.0	0.0	0.0	0.0	5.7
NE	1.4	0.7	0.1	0.0	0.0	0.0	0.0	2.2
ENE	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.7
E	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.6
ESE	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.4
SE	0.7	0.7	0.3	0.0	0.0	0.0	0.0	1.8
SSE	1.5	3.8	2.7	0.5	0.1	0.0	0.0	8.6
S	2.6	6.9	7.6	1.9	0.4	0.1	0.0	19.5
SSW	0.8	0.6	0.6	0.2	0.1	0.0	0.0	2.2
SW	0.5	0.2	0.1	0.0	0.0	0.0	0.0	0.8
WSW	0.4	0.2	0.1	0.0	0.0	0.0	0.0	0.6
W	0.7	0.3	0.1	0.0	0.0	0.0	0.0	1.1
WNW	0.7	0.3	0.1	0.0	0.0	0.0	0.0	1.1
NW	2.3	1.3	0.3	0.0	0.0	0.0	0.0	3.9
NNW	5.2	4.0	0.5	0.0	0.0	0.0	0.0	9.7
Total (%)	30.4	30.9	14.1	2.8	0.6	0.1	0.0	78.9

Total Hours: 587295
Total Observations: 586945
Missing Observations: 350
Calm Observations: 123617
Percent Missing: 0.1 %
Percent Calm: 21.0 %

Figure 4-1 Wind rose plot - Penticton station.

Kelowna - Primarily northerly (N) and southerly (S) winds (Figure 4-2). South southeasterly (SSE) and north northwesterly (NNW) winds were also recorded. Station is located west of Okanagan Lake, sheltered to the west by Mount Knox and McKinley Mountains. The valley and lake have similar orientation at this location. Wind magnitude might not be representative of the of the wind conditions over Okanagan Lake near Kelowna.



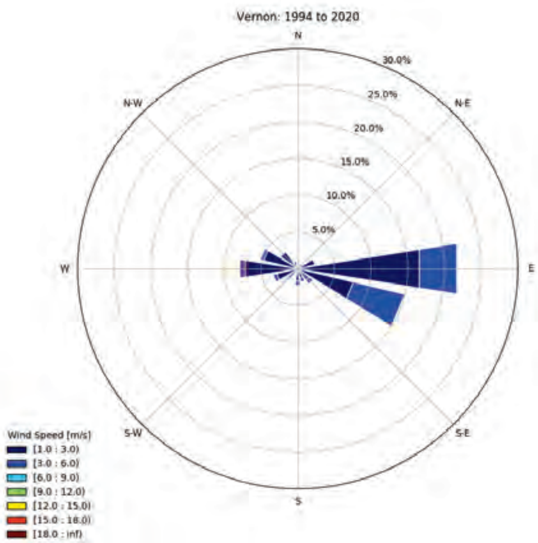
Wind Speed and Direction Frequency Distribution

	1 - 3	3 - 6	6 - 9	9 - 12	12 - 15	15 - 18	> 18	Total (%)
N	7.1	4.1	0.7	0.1	0.0	0.0	0.0	12.0
NNE	3.5	0.4	0.0	0.0	0.0	0.0	0.0	3.9
NE	2.5	0.1	0.0	0.0	0.0	0.0	0.0	2.6
ENE	1.4	0.1	0.0	0.0	0.0	0.0	0.0	1.4
E	1.3	0.1	0.0	0.0	0.0	0.0	0.0	1.4
ESE	1.1	0.3	0.0	0.0	0.0	0.0	0.0	1.4
SE	2.9	1.6	0.2	0.0	0.0	0.0	0.0	4.6
SSE	3.9	2.5	0.2	0.0	0.0	0.0	0.0	6.7
S	6.1	3.0	0.5	0.0	0.0	0.0	0.0	9.7
SSW	2.3	1.2	0.4	0.0	0.0	0.0	0.0	3.9
SW	1.3	0.7	0.3	0.0	0.0	0.0	0.0	2.3
WSW	0.7	0.3	0.1	0.0	0.0	0.0	0.0	1.1
W	0.7	0.2	0.0	0.0	0.0	0.0	0.0	0.9
WNW	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.6
NW	1.1	0.6	0.1	0.0	0.0	0.0	0.0	1.9
NNW	2.3	2.4	0.7	0.1	0.0	0.0	0.0	5.5
Total (%)	38.6	17.9	3.3	0.3	0.0	0.0	0.0	60.2

Total Hours: 532768
Total Observations: 456040
Missing Observations: 76728
Calm Observations: 165453
Percent Missing: 14.4 %
Percent Calm: 36.0 %

Figure 4-2 Wind rose plot - Kelowna station.

Vernon – winds predominantly easterly (E) and east southeasterly (ESE) (Figure 4-3). Westerly (W) winds were also recorded. Wind station located between Okanagan Lake and Lavington. O`Keefe and Commonage Mountains located west of the station. Wind sampled at this location follows the orientation of Lavington valley heading east towards Lumby, and directions are not expected be representative of the wind conditions at the northern end of Okanagan Lake.



Wind Speed and Direction Frequency Distribution

	1 - 3	3 - 6	6 - 9	9 - 12	12 - 15	15 - 18	> 18	Total (%)
N	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.7
NNE	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.7
NE	0.9	0.1	0.0	0.0	0.0	0.0	0.0	1.0
ENE	2.4	0.1	0.0	0.0	0.0	0.0	0.0	2.5
E	16.8	5.2	0.0	0.0	0.0	0.0	0.0	22.0
ESE	7.8	7.2	0.1	0.0	0.0	0.0	0.0	15.1
SE	1.9	0.7	0.1	0.0	0.0	0.0	0.0	2.7
SSE	1.3	0.6	0.0	0.0	0.0	0.0	0.0	1.9
S	1.6	0.6	0.0	0.0	0.0	0.0	0.0	2.3
SSW	0.6	0.2	0.1	0.0	0.0	0.0	0.0	0.9
SW	1.3	0.4	0.3	0.1	0.0	0.0	0.0	2.1
WSW	2.9	0.5	0.1	0.0	0.0	0.0	0.0	3.6
W	7.2	0.7	0.1	0.0	0.0	0.0	0.0	8.1
WNW	4.7	0.5	0.0	0.0	0.0	0.0	0.0	5.3
NW	2.8	0.2	0.0	0.0	0.0	0.0	0.0	3.1
NNW	1.0	0.1	0.0	0.0	0.0	0.0	0.0	1.1
Total (%)	54.3	17.3	1.1	0.2	0.0	0.0	0.0	73.0

Total Hours: 227616
Total Observations: 225796
Missing Observations: 1820
Calm Observations: 60792
Percent Missing: 0.8 %
Percent Calm: 26.0 %

Figure 4-3 Wind rose plot - Vernon station.

Peak Over Threshold Analysis

The peak over threshold analysis conducted for each station is based on a 12-hour interval between events for each predominant wind direction. The threshold values are listed in Table 4-2. Sensitivity of the results was assessed by changing the time interval to 24-hr. No variation was observed.

Table 4-2 Peak Over Threshold Analysis summary.

Area	Event	Wind Direction (˚)	Threshold Wind Speed (m/s)	Storm Duration (hr)
Penticton	Southerly	135-220	16.00	12
	Northerly	330-30	11.50	12
Kelowna	Southerly	135-220	10.95	12
	Northerly	330-30	11.00	12
Vernon	Westerly	240-320	5.50	12
	Easterly	60-135	6.00	12

Vernon station recorded westerly and easterly winds. Westerly events were assumed to co-occur with southerly event at Penticton and Kelowna. Similarly, easterly events were considered to co-occur with northerly events at Penticton and Kelowna. Concurrent southerly and northerly events at each station, and the corresponding wind speed and direction are summarized below and in Table 4-3 and Table 4-4, respectively.

4.2.3 Southerly Events

- Peak storms occur during the fall/winter season (October-February).
- At Penticton, the wind directions associated with storm events follows the valley orientation. Design wind direction: 180˚.
- Peak events at Kelowna are from an SSE direction (150-160˚). This is likely due to the station location west of Okanagan Lake. McKinley Landing and Ellington Mountains located between the station and the lake create a separate valley following an SSE orientation. For design, a SW-SSW wind direction has been chosen (2011 and 2019 events). Design wind direction: 190˚.
- Peak events at Vernon are from WSW direction (250-260˚), following west-east orientation of Lavington valley. It is assumed that wind directions over the north end of Okanagan Lake are aligned with the main valley for winds: 205˚ (based on Okanagan Lake orientation). The wind magnitudes were not adjusted, only the direction. It is unclear how representative the Vernon wind velocity measurements are with respect to wind velocity over the lakes.
- No information of the elevation of Penticton wind station was available and a standard station elevation of 10 m above ground was assumed. Elevation corrections were therefore not applied to design wind speeds. Over land to over water wind speed adjustments were not applied as both southerly and northerly 200-year design events have a magnitude greater than 18.5 m/s (correction factor <1).

Table 4-3 Historical southerly events.

Penticton			Kelowna			Vernon		
Date y/m/d/h	Wind Speed (m/s)	Wind Direction (˚)	Date y/m/d/h	Wind Speed (m/s)	Wind Direction (˚)	Date y/m/d/h	Wind Speed (m/s)	Wind Direction (˚)
1963/10/21/4	22.2	180	1963/10/21/13	15.6	160			
2001/12/15/21	18.1	190	2001/12/15/23	11.4	150			
1963/10/24/6	17.8	180	1963/10/24/7	13.3	160			
1996/12/4/17	16.9	180	1996/12/4/11	12.2	150			
2008/11/21/22	16.4	190	2008/11/21/17	11.4	140			
2009/11/19/1	16.4	190	2009/11/19/22	12.8	150			
2012/1/24/20	16.4	190				2012/1/25/7	5.3	250
2014/2/12/5	16.1	190				2014/2/13/14	5.6	260
			2011/4/11/14	11.4	210	2011/4/11/13	6.1	250
			2016/3/10/12	14.4	190	2016/3/10/14	6.1	250

4.2.4 Northerly Events

- Peak storms occur during the fall/winter season (September-April).
- At Penticton, the wind directions associated with storm events follow the valley orientation. Design wind direction: 0˚.
- At Kelowna wind directions associated with storm events follow the valley orientation. Design wind direction: 0˚.
- Peak events at Vernon are from ESE direction (110˚), following east-west orientation of Lavington valley. Design wind direction: 20˚ (based on Okanagan Lake orientation).
- No information of the elevation of Penticton wind station was available and a standard station elevation of 10 m above ground was assumed. Elevation corrections were therefore not applied to design wind speeds. Over land to over water wind speed adjustments were not applied as both southerly and northerly 200-year design events have a magnitude greater than 18.5 m/s (correction factor <1).

Table 4-4 Historical northerly events.

Penticton			Kelowna			Vernon		
Date y/m/d/h	Wind Speed (m/s)	Wind Direction (˚)	Date y/m/d/h	Wind Speed (m/s)	Wind Direction (˚)	Date y/m/d/h	Wind Speed (m/s)	Wind Direction (˚)
1971/10/13/12	16.1	360	1971/10/13/11	11.1	360			
1959/4/23/10	15.6	20	1959/4/23/11	11.1	360			
1972/4/1/15	15.3	360	1972/4/1/14	13.3	350			
2012/1/10/8	15.0	350	2012/1/10/8	11.4	330			
1989/1/31/2	14.4	340	1989/1/31/11	12.8	350			
1991/10/21/11	14.4	350	1991/10/21/9	13.9	330			
1964/12/15/15	13.3	360	1964/12/15/16	11.7	340			
1974/9/26/7	12.5	330	1974/9/26/7	11.1	350			
2019/10/7/23	11.7	10	2019/10/7/22	15.3	340			
			2012/5/25/11	11.4	350	2012/5/25/23	6.1	110

4.2.5 Extreme Value Analysis

ARI events were calculated based on the peak over threshold analysis results, following the methodology summarized in Goda (2000) for data following a Gumbel distribution. ARI events and corresponding wind speeds are summarized in Table 4-5 for each station, for the site-specific predominant wind directions.

Table 4-5 ARI for design events at all wind stations.

ARI (years)	Penticton		Kelowna		Vernon	
	Northerly	Southerly	Northerly	Southerly	Westerly	Easterly
1	12.3	16.6	11.9	11.4	5.3	6.3
2	13.8	17.7	12.8	12.6	5.6	6.4
5	15.4	18.9	13.8	13.7	5.9	6.6
10	16.5	19.8	14.6	14.5	6.2	6.8
20	17.6	20.6	15.3	15.3	6.4	6.9
50	19.0	21.6	16.3	16.3	6.7	7.1
100	20.0	22.4	17.0	17.1	7.0	7.2
200	21.1	23.2	17.7	17.8	7.2	7.3

4.2.6 Atmospheric Pressure Data

Given the length of Okanagan Lake, it was deemed necessary to determine if a pressure gradient exists across the lake from the north end to the south end. The atmospheric pressure variation at the three stations was assessed to determine pressure probability distribution and variation of pressure during storms (record extremes) and calm weather. Based on the stations' elevations and comparison of records during storm and calm weather, the difference in pressure is not affected by wind magnitude or direction. Any pressure difference observed can be related to the difference in elevation of the stations. Thus, the data does not indicate there are strong pressure gradients across Okanagan Lake that could lead to significant differences in lake levels.

4.2.7 Seasonal Design Wind Event

Spatially-Varying Wind Field

Spatially-varying wind fields representative of northerly and southerly wind events were synthesized manually, by following the natural orientation of the lake and Okanagan valley. A spatially-varying wind field from an atmospheric model was considered for the basin, but extreme wind events during the flood peak times was not available for the dates that were available on record.

An example of Okanagan Lake's synthesized wind field shown in Figure 4-4. The details of the wind field are as follows:

- Wind Field Resolution: 2,500 m
- Width (x): 45,000 m
- Length(y): 120,000 m

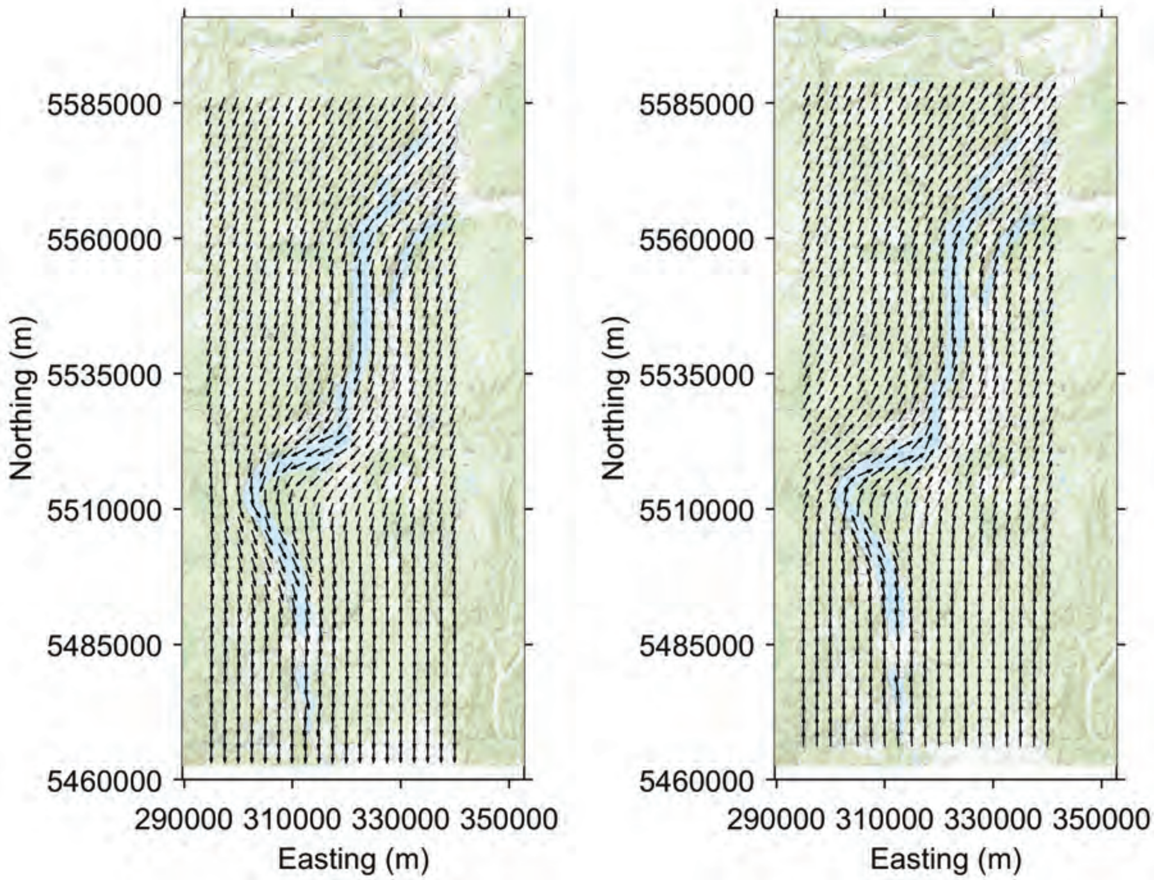


Figure 4-4 Synthesized wind fields for northerly (left) and southerly (right) events. Note that only the wind vectors over the lakes are used in the wave model analysis, and for this reason wind vectors away from the lakes are not relevant.

Analysis of Seasonal Extremes

The wind analysis was repeated for just the flood season (March – August) to determine wind magnitudes for a storm that was likely to occur during the actual times of flooding on the OLRS. The ARI events were calculated based on the peak over threshold analysis results for March -August, following the methodology summarized in Goda (2000) for data following a Gumbel distribution. ARI and corresponding wind speeds for flood seasons are summarized in Table 4-6. The thresholds are northerly 10 m/s and southerly 12 m/s. Storm event thresholds have been chosen such that at least 1 storm occurs every 2-3 years in the wind records. The Penticton location was chosen to represent the entire wind field as it has the highest seasonal winds.

Table 4-6 ARI of seasonal design events and confidence intervals for Penticton.

ARI (years)	Penticton					
	Northerly			Southerly		
	Wind Speed (m/s)	90% Confidence Interval Upper Bound (m/s)	90% Confidence Interval Lower Bound (m/s)	Wind Speed (m/s)	90% Confidence Interval Upper Bound (m/s)	90% Confidence Interval Lower Bound (m/s)
1	10.4	10.7	10.2	13.2	13.4	13.1
2	12	12.3	11.7	14.3	14.5	14.1
5	13.7	14.2	13.2	15.5	15.8	15.2
10	14.9	15.5	14.3	16.4	16.8	16
20	16	16.8	15.3	17.3	17.7	16.8
50	17.5	18.4	16.7	18.4	19	17.9
100	18.7	19.7	17.7	19.3	19.9	18.6
200	**19.8**	21	18.7	**20.1**	20.8	19.4

Comparison to Observation Data

A larger study on evaporation and development of a mass transfer model for water management purposes was conducted for Okanagan Lake by Spence and Hedstrom (2015). Three buoys were deployed across the length of Okanagan Lake for the duration of their study (July 2011 – May 2014). These buoys supported remote meteorological stations and were collecting wind data as part of the study. Wind Roses were developed based on the data they had collected at the stations and can be seen in Figure 4-5 below. The thick white line represents the relative frequency with which wind blows from each 10 degrees of compass direction. The red dots represent buoy locations. The wind roses show that the prevailing winds on the lake closely follows the orientation of the lake valley. These observations validate the decision to align the wind direction in the synthetic wind fields to the shape of the valley and the lake.

When considering magnitude, the largest storms are at Penticton from the south and occur primarily in winter (section Figure 4-6). The winds at Kelowna are much weaker than those at Penticton and calm during a greater percentage of time. The Kelowna airport is located in the next valley to the east and is sheltered by topography. As such, it is not representative of the winds over the lake. The Vernon wind station is located at the head of Kalamalka Lake, in the same valley as Kelowna airport and similarly is not a good indicator of the winds over the lake.

Wind data for the overlapping period between Penticton airport station and weather buoy stations were examined. Several larger storm events (greater than 16 m/s at Penticton with an ARI of roughly a 1 year (Table 4-5)) occurred in this period with comparable data. Figure 4-6 shows the wind stick plots from one event (February 2014) with the four stations over the course of this event and several other small events after. The results show that the wind speeds measured at the buoys are less than those observed at Penticton during the peak of the storm, but they do share events with similar magnitudes across all stations. With limited data that is required to establish proper correction between stations and to err on side of caution, it is decided to use Penticton Airport data for the seasonal design wind event.

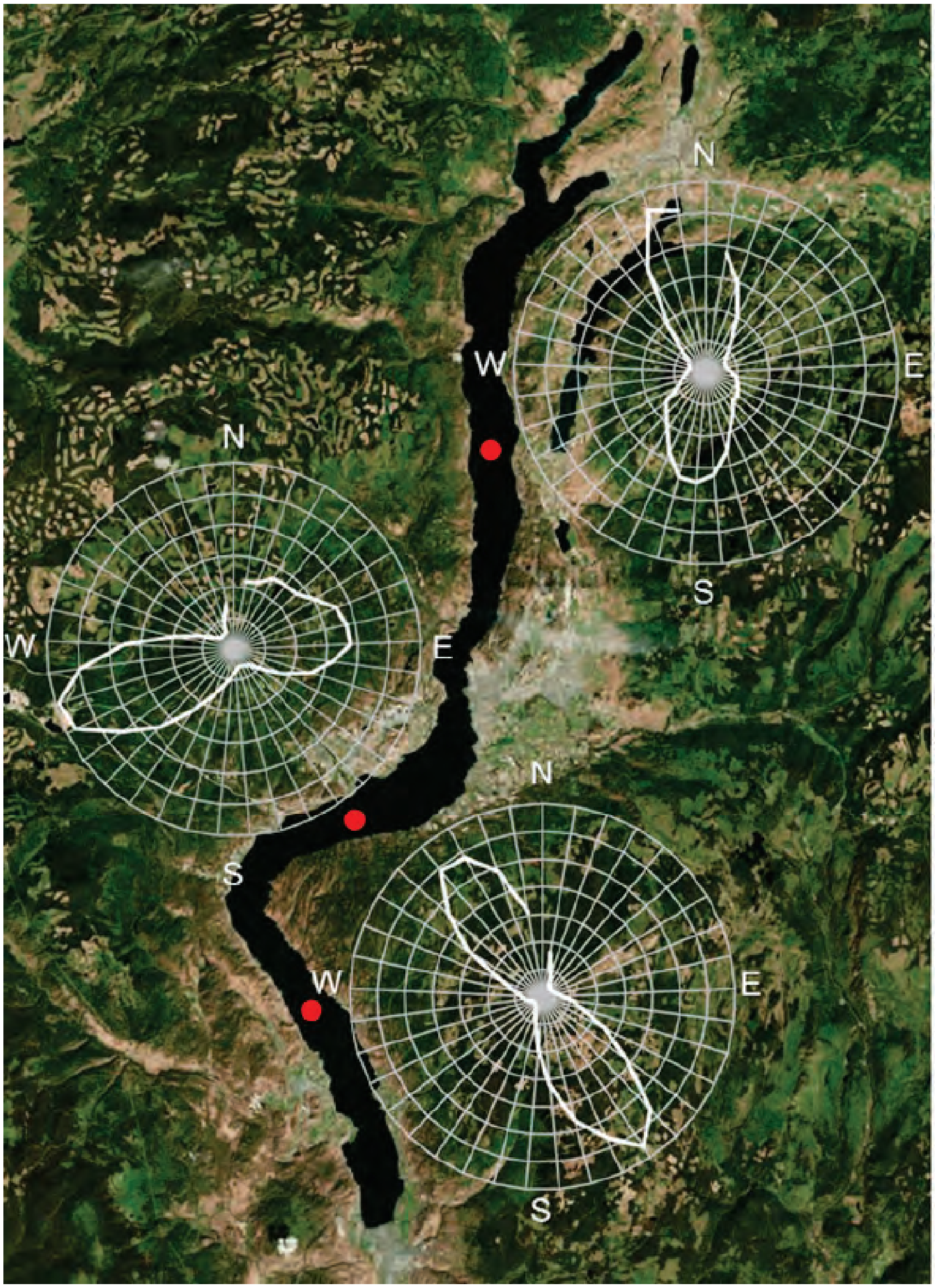


Figure 4-5 Wind roses from Spence and Hedstrom (2015)'s weather buoys on Okanagan Lake.

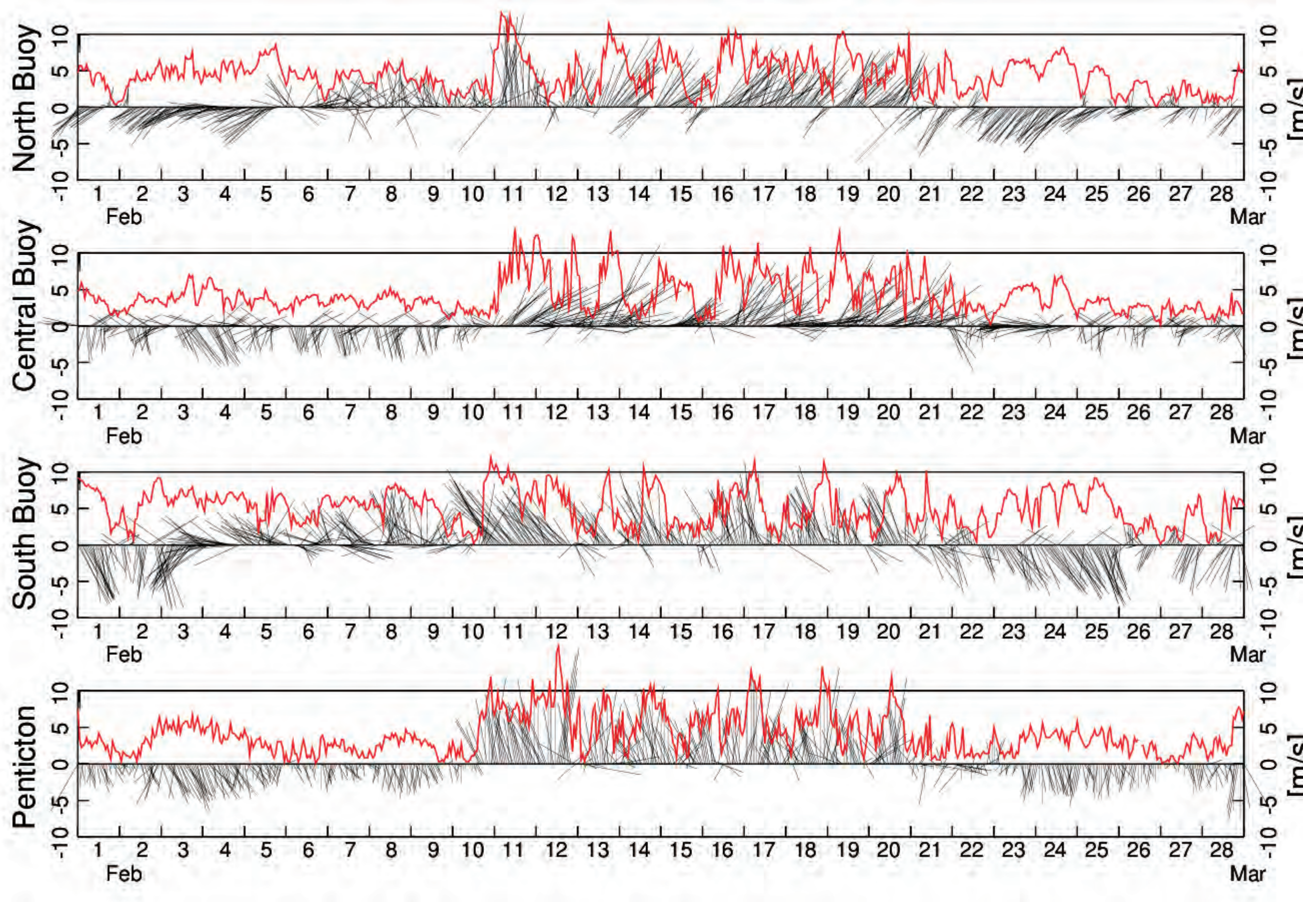


Figure 4-6 Wind stick plots (direction, date-time, and magnitude) from the 3 buoy stations (Spence and Hedstrom, 2015) and Penticton over the 2014 peak event.

4.3 Simulation of Waves on Lakeshores

NHC developed wave models in-house for each of Okanagan, Wood-Kalamalka, Skaha, Vaseux and Osoyoos lakes to simulate wave generation and propagation on the lakes. The SWAN model (Simulating Waves Nearshore or SWAN, version 41.20) has been used which incorporates physical processes such as wave generation by wind, wave propagation, white-capping, shoaling, wave breaking, bottom friction, sub-sea obstacles, wave setup and wave-wave interactions in its computations (Booij, N. et al., 2004).

A separate model grid for each lake was used with model grid resolutions of 50 m for Okanagan lake and 25 m for all other lakes. The model's bathymetric grids were generated from a digital elevation model (DEM) that includes a combination of BC Ministry of Environment (MOE) Fish and Wildlife Service (BC Ministry of Environment, 2019) and Canadian Hydrographic Charts (see section 5.2 for details).

The 200-year ARI wind events for each design direction (northerly and southerly) were used to force the SWAN model. For each event, a spatially varying wind field was developed and applied to both the coarse and fine grid models. The results of the SWAN simulation can be seen in Figure 4-7.

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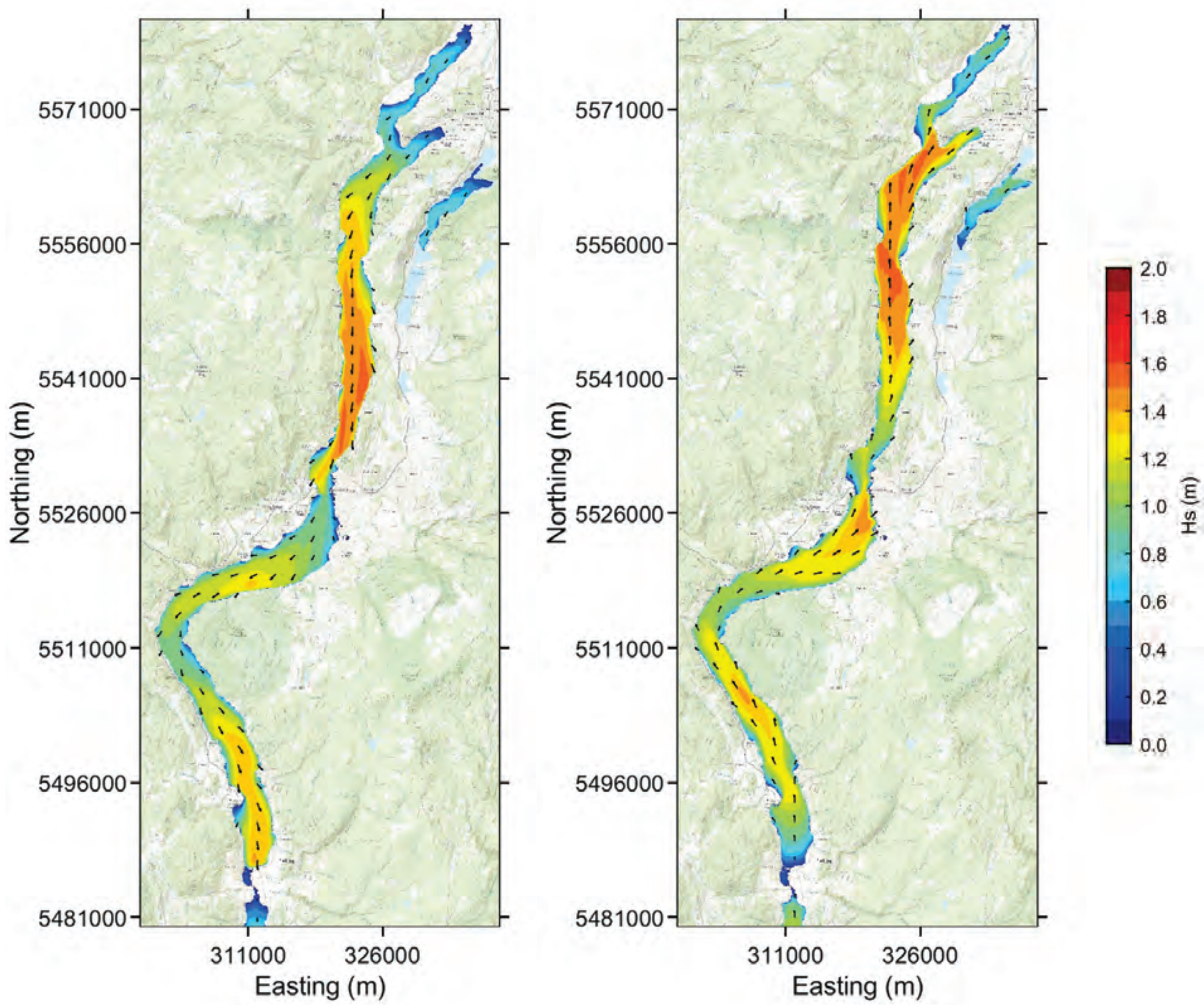


Figure 4-7 SWAN significant wave height results for Okanagan Lake for northerly (left) and southerly (right) design wind storms.

4.3.1 Analysis of Wave Effects

As waves approach the shoreline they steepen as they reach shallower water and eventually break as the water depth becomes too shallow for the wave height. The breaking waves can continue to runup the slope, limited by ground slope, roughness, and porosity. In addition, spray from the waves, particularly from the breaking waves, can splash or be blown shoreward. The limits on wave runup at the shoreline determines the extent and elevation over which waves act. Wave runup is therefore an important parameter to determine flood inundation extents from storms. Following the provincial guidelines (BC MoE, 2011), the two percent wave runup ($R_{2\%}$), which is the runup that only two percent of the wave runup values observed will reach or exceed, associated with the design storm event, is used to assess the wave effect.

The wave runup for each section was estimated using either the method described in European Overtopping Manual (EurOtop, 2018) or the method described in the USACE- Coastal Engineering Manual (CEM) (US Army Corps of Engineers, 2002). The CEM method is specifically for beaches with shallower slopes (<12%). The results are shown in Table 4-7; the values were applied to determine the FCL values for the design event on the shorelines. It is assumed in this analysis that the future foreshore slope and beach materials will be the same as that of the existing foreshore, and changes to the foreshore slopes would change the FCL.

Table 4-7 Wave effects estimated for study area for each wave effects zone.

Lake	Zone	Wave Properties			Shoreline Properties		Effect
		Significant Wave Height (Hs) (m)	Mean Wave Period (Tm) (sec)	Peak Wave Period (Tp) (sec)	Depth at the Toe (m)	Slope	R2% Wave Runup (m)
Okanagan	Zone 1	1.2	3.0	4.1	1.9	15%	1.4
Okanagan	Zone 2	1.1	3.1	4.1	2.1	40%	2.1
Okanagan	Zone 3	1.1	3.0	4.1	2.2	10%	0.9
Okanagan	Zone 4, 6, 8	1.6	3.8	5.1	2.3	40%	2.7
Okanagan	Zone 5	1.3	3.4	4.6	2.1	30%	1.8
Okanagan	Zone 7	1.3	3.4	4.6	1.9	25%	1.5
Kalamalka Lake	Zone 1	0.8	2.6	3.6	1.5	20%	0.8
Wood	Zone 1	0.9	2.5	3.3	1.4	10%	0.9
Wood	Zone 2	0.9	2.5	3.3	1.4	60%	1.9
Ellison	Zone 1	0.8	2.4	2.7	1.3	20%	1.0
Skaha Lake	Zone 1	1.0	2.9	3.7	2.0	30%	1.5
Skaha Lake	Zone 2	0.9	2.7	3.7	2.0	30%	1.2
Skaha Lake	Zone 3	0.7	2.4	3.7	1.0	5%	0.6
Skaha Lake	Zone 4	0.9	2.8	4.1	1.2	25%	0.9
Vaseux	Zone 1	0.6	2.0	2.6	1.3	10%	0.7
Osoyoos	Zone 1	0.7	2.4	3.3	2.4	20%	0.8

It is important to note that wave runup is largely governed by the geometry of the shoreline. A gentle sloping shoreline with vegetation will experience much lower levels of wave runup than a seawall for example. This is graphically shown in the photo below taken along the West Vancouver waterfront during a moderate storm occurring at an extremely high tide. The gentle shoreline where the photographer is standing is experiencing minor wave runup whereas the seawalls are experience wave runup in excess of 2m elevation.

Figure 4-8 Photo of wave runup in West Vancouver (credit: NHC).

It is noted that wave effects are limited to the area immediately adjacent to the shoreline and that for areas that are relatively flat the wave runup effect does not extend large distances inland as waves break near the shoreline and propagate landward as spilling waves that are reduced in height by interactions with vegetation, structures, and such. Thus, a shoreline FCL that includes wave effect is not necessarily an appropriate FCL for properties at similar elevations that are 40 m or more setback from the shoreline where large waves are breaking. In those cases, the depth of flooding is governed by the lake inundation, volume of wave overtopping, and the site drainage.

4.4 Potential for Tsunami-Driven Waves

4.4.1 Overview

In addition to wave and storm events, high water and shoreline inundation could potentially occur from a tsunami event resulting in localized flooding and property damage. Previously denoted as tidal waves, the Japanese term tsunami is now used to denote long period waves (5 to 60 minutes) that radiate out from the rapid displacement of a large volume of water. The displacement is triggered by a large impulse of energy and, as such, can result from a wide variety of sources such as: earthquakes, landslides, volcanic eruptions, glacier calving events, or impacts from a meteorite. Major tsunami events generally are a result of earthquakes that produce substantial vertical movement of the sea floor in sufficiently shallow water. This requirement is why a substantial portion of the most notable tsunamis occur in the active tectonic margin surrounding the Pacific Ocean (e.g. 1700 Japan, 1963 Alaska, 2004 India, and 2011 Japan).

While earthquakes are the source for more than 80% of all documented tsunami events, landslides constitute the second-most important cause of tsunamis (Løvholt et al., 2015). Despite the comparatively low risk for landslides in the Okanagan Valley relative to Coastal BC, the combination of steep bedrock slopes and poorly consolidated silt bluffs make landslides the leading reported geological hazard in the region (AE, 2017). Were a landslide to enter one of the lakes, it could potentially generate a Tsunami. This section evaluates the history of landslides and landslide-generated waves around

Okanagan Lake and potential triggers for future tsunami waves based on the geologic setting and seismic risk in the valley.

4.4.2 Landslide Induced

While terrestrial tsunamis are rarer than their oceanic counterparts, subaerial landslides in waterbodies can produce devasting waves that have claimed the lives of thousands around the world (Løvholt et al., 2015). These typically occur in mountain lake basins and reservoirs where landslides are triggered on slopes due to earthquakes, poor drainage, and over-steepening. Recovery of a landscape in response to deglaciation may also contribute to the mass failure of material; collapse of the Taan Fiord valley cause a tsunami to form in 2015 (Higman et al., 2018). Lake tsunamis have the potential to be more damaging than those on the coast because lakes are closed systems. The maximum height of the wave can be substantially higher than that possible at the coast because of basin constraint, for example the Mt. St. Helens -caused Spirit Lake tsunami reached 260 m (Voight et al., 1983). In addition, instead of a single series of waves, lake tsunamis can generate seiches, standing waves that can oscillate in the enclosed water body for hours (Ichinose et al., 2000).

Perhaps the best local example is the December 2007 Chehalis Lake tsunami, where a 3 million cubic meter rockslide entered the north end of the lake and generated a tsunami with local runup exceeding 35 meters. While the entire 8.5 km-long shoreline was altered, the tsunami had the greatest impact on low-gradient shores and those areas closest to the slide (NHC, 2008a; Roberts et al., 2013). In 1959 an earthquake triggered a seiche in Hebgen Lake, where oscillating waves propagated for hours overtopped the dam. Other international examples include the 2003 Three Gorges Reservoir Gongjiafang landslide and river tsunami that claimed the lives of 14 people from the 20-m wave, and the 1963 landslide generated tsunami in the Vajont Dam reservoir in Italy, where a wave overtopped the dam and killed over 2000 people downstream (Dai et al., 2004; Wolter et al., 2016).

Only two cases of landslide-generated tsunami waves in Okanagan Lake have been documented (Table 4-8; Tannant, 2011) with wave heights ranging from 1.5 to 4 meters. The tsunami wave overtopped a home in the 1951 event, fortunately without any casualties. While sliding mass volumes have not been well-documented, the 2008 Goat Bluff landslide suggests that tsunami-triggering large slides and rockfalls along the lake perimeter are possible. The Goat Bluff slide occurred during construction of Highway 97 road widening along a steep roadcut between Peachland and Summerland. Excavation at the toe activated a tensile fracture upslope, producing a 150,000 m^3 sliding mass capable of dropping into the lake (Bean and Oldrich, 2011). The potential mass movements, and subsequent tsunami hazard, were avoided through unloading and stabilizing the at-risk slope.

Table 4-8 Notable landslides along the Okanagan Lake margin.

Date	Location	Wave Height (meters)	Description
8/3/1942	Across Lake from Summerland (exact location unknown)	1.5	3 waves traveled across lake to Summerland causing damage to docks, piers and cabins
7/20/1951	Poplar Grove	4	Tsunami wave washed over a house along the shoreline
8/20/1969	Old Agricultural Research Station	-	Consecutive slides in Dec 1971 and 1974
3/14/1975	Lake Okanagan Provincial Park	-	Activated on access road on silt bluff
9/15/1992	Summerland	-	Silt bluff slide travelled across road burying shoreline garage in 5 m of silt
10/23/2008	Goat Bluff (Hwy 97 between Summerland and Peachland)	-	150,000 m^3 sliding mass pre-emptively unloaded to prevent full slide and tsunami wave

The nature of landslide-triggered tsunami waves has been studied in physical laboratories and through geomorphic evidence. (McFall and Fritz, 2016) analyzed the effects of the lateral hill slope curvature and landslide granulometry on the offshore wave characteristics of tsunamis using a physical model of gravel and cobble slide sources. Results suggest that bulkier materials produce larger wave amplitudes and that, on average, the leading wave crest is larger when generated on a planar rather than convex conical hillslope. This presents a complicated implication for Okanagan Lake, where the main slide material is fine granular silt and sand and the sliding surfaces planar, as these two features will act against each other. Although a landslide of glaciolacustrine silts may not trigger as large of a wave as sliding bedrock, the total destructive force of a wave depends not only on granularity and slope, but also on landslide impact velocity, acceleration, and the total displacement volume and frontal area (Løvholt et al., 2015). In the event of retrogressive slides[1] with multi-staged release, the prolonged period of material input further complicates wave behavior prediction.

4.4.3 Regional Geology and Seismicity

Okanagan Lake is the remnant of ancestral Lake Penticton, a large glacial lake from the most recent Fraser Glaciation. The tall and steep silt bluffs and erosional scarps that border the lake are a product of numerous punctuated lowering of the ancient lake. Landslides in silt and sand glaciolacustrine sediment are well-documented in the literature (e.g. Desloges and Gilbert, 1994; Marko et al., 2010). Cited landslide triggers in the region include improper drainage from upslope agricultural lands, natural elevated water levels, and oversteepening of slopes. There are no known recorded events of

[1] In a retrogressive landslide the rupture surface is extending in the direction opposite to the movement of the displaced material, http://www.ukgeohazards.info/pages/eng_geol/landslide_geohazard/eng_geol_landslides_classification.htm, accessed 31 March 2020.

earthquake-triggered landslides in the valley, yet small earthquakes are frequent and may potentially provide the trigger for at-risk slopes. The north-south striking Okanagan Valley Normal Fault runs through Okanagan Lake down the center of the valley into Skaha Lake, resulting in contrasting bedrock lithologies below the valley fill of glaciolacustrine silts and glacial till. The fault separates metamorphic and plutonic bedrock on the eastern foot wall with volcanic, plutonic, and less competent sedimentary rocks on the western hanging wall. In various locations, particularly Summerland, this tertiary claystone provides for a weak failure plane in which multiple landslides have and continue to occur. Summerland's 'Perpetual Landslide' is perhaps the best example of this (Riglin, 1977). The Valley-striking fault has been inactive for 20 million years, putting the fault at low risk of rupturing (Roed and Fulton, 2019).

According to the 2015 National Building Code of Canada the Okanagan Valley falls within a low seismic risk zone. The threat of severe shaking from a large earthquake is therefore low in the tectonically inactive valley. Small earthquakes are common, with Penticton experiencing around 12 quakes per year between Magnitude 2 to 4 (See Figure X; Natural Resources Canada, 2020), however, discussion on the tectonic triggers of these quakes is missing from the literature. A likely cause of these frequent yet small quakes is stress transfer from the convergence of the North American and Pacific Plates, with energy traveling hundreds of kilometers through the crust to reactive small faults (Steacy, 2005; Stein, 2003). Despite the near location of quakes in the valley, distant large quakes in Washington and Coastal BC have caused the most damage to the Okanagan Valley in the recorded past.

Estimating the risk of an earthquake-triggered landslide capable of producing tsunami waves in Okanagan Lake is challenging given the lack of cited earthquake-triggered slides in the valley. Solely based on the likelihood of earthquakes large enough to cause failures on their own, the risk appears to be very low. Risk, however, increases when the possibility of seismic activity coincides with areas of instability; those with Factors of Safety approaching 1. Given the record of terrain instabilities along the lake margin and the probability of distal large quakes near the coast, the threat is still present. Specifically, in the Okanagan Valley, this would likely occur when slopes experience peak seepage discharge and pore pressure is at a maximum, minimizing resistive stresses. Ongoing proactive measures including transitioning to drip irrigation and development restrictions reduce this risk, but do not preclude it (AE, 2017a).

4.5 Conclusions, Recommendations, and Future Work

Generalized wave effects have been calculated for zones with similar terrain along each lake. This value should be added to the lake FCL for near shore locations. While the winds varying across the valley, Penticton was a suitable choice for the seasonal design storm combined with a synthetic spatially-varying wind field. These inputs were used to drive the wave modelling and provide input for the wave effects analysis which informs the flood mapping and FCL development. The wave results are limited by the accuracy of all data used in the modelling. The bathymetry available for several of the lakes is particularly coarse and bathymetric surveys (particularly in the nearshore) could improve the accuracy of the nearshore wave results.

It is recommended that any major developments or any change to the existing shoreline profiles require a site-specific analysis to determine a new appropriate wave runup and a new FCL. Residents or developers could also complete specific flood hazard assessments to refine the FCL for their specific location if they so chose. It is recommended that site specific hazard assessment or design include refinement of wave effects based on local bathymetry, and shoreline slope, roughness, and porosity.

For future work, improvements to the bathymetric data for all the lakes should be considered with a focus on the nearshore. This could be used to improve wave results and improve site specific analysis.

Landslide generated tsunamis have been documented in Okanagan Lake over the last 80 years and can result in runup in excess of that calculated for the wind generated wave events. More detailed study of potential landslide zones, the generation and propagation of tsunamis, and subsequent runup zones should be conducted and added to the floodplain maps. Further work is recommended in assessing tsunami hazard in the Okanagan Valley overall, and that this be provided at minimum as information on floodplain maps or included in FCLs where relevant.

CHAPTER 5 RIVER FLOODPLAIN

5.1 Chapter Synopsis

In BC, the 1:200 ARI instantaneous peak flow or the flood of record, whichever is greater, is typically used to define the local flood hazard for floodplain mapping. The 200-year unregulated (gates open) mid-century climate change scenario was selected as the design flood for the Okanagan River following on recommendations in Chapter 3 Hydrology.

Data was collected from a wide variety of sources including river surveys, hydraulic structure surveys (dams and bridges, etc.), bathymetric surveys of the lakes, Lidar, orthoimagery, and WSC gauges. It was used to develop, calibrate and validate a river hydraulic model in HEC-RAS software (the US Army Corps of Engineers Hydraulic Engineering Centre's River Analysis System) that extends from Okanagan Lake to Osoyoos Lake. The hydraulic model includes all the vertical drop structures, bridges, and culverts without flap gates within the river reach. McIntyre Dam is also included in the model extents. Okanagan Lake Dam and Okanagan Falls Dam are not included in the model.

The model results were compared with past observations from the 2017 and 2018 floods to verify the model prior to simulation of the design flood. The design flood and additional events were simulated with the outputs from the Raven model to develop flood extents for the river.

Several hydraulic model parameters were varied within reasonable limits to test the sensitivity of the model as a step to understand and address potential systematic errors from the simulations.

5.1.1 Limitations on the River Floodplain Component of this Study

The hydraulic model is limited by the accuracy of the available data and the assumptions implicit in the hydraulic model. Please see section 5.5.1 for more details.

5.2 Data Sources

Numerous data sets have been received and compiled for the hydraulic modelling. These data sets, usage, and any associated assumptions are described below. Unless noted otherwise, all data was delivered in the project standard datums of UTM Zone 11, NAD83 and CGVD2013.

Topographic and Bathymetric Survey Data

Survey data was provided by WSP Global Inc. The survey data includes bathymetry for the Okanagan River at historic cross sections locations. The survey captured:

- 43 cross sections along the Okanagan River from Okanagan Lake to Skaha Lake,
- 40 cross sections from Skaha Lake to Vaseux Lake, and
- 202 cross sections from Vaseux Lake to Osoyoos Lake.

The survey was completed during March and June of 2019. The survey points captured the geometry of the channel but also extended overbank to overlap and tie-in with the Lidar. The survey was conducted using a combination of post-process RTK GPS. USGS and WSC gauge benchmarks in the Okanagan Basin were also surveyed by WSP Global Inc. in order to convert the station data to the CVGD2013 datum. Hydraulic structures (vertical drop structures, bridges, culverts, dams) and flood control structures, such as dikes, were not captured by the ground survey.

Hydraulic Structures

There are a number of hydraulic structures within the study reach, including dams, vertical drop structures (VDS), bridges, and culverts. The hydraulic structure elevations and dimensions were extracted from the report and hydraulic model created by WaterSmith Resource Inc. and Streamworks Consulting Inc. (2014). The hydraulic structures were surveyed by Okanagan Survey & Design Ltd (sub-contracted to WaterSmith Resource Inc.) in the winter and early spring of 2014 using a combination of RTK GPS and conventional (total station) survey methods. Maximum vertical uncertainty was stated to be 0.02 m. The hydraulic structures extracted from the report and hydraulic model are listed below.

Vertical Drop Structures:

- VDS 1 through 17 (where VDS structures have decks (road crossing), decks were not included in the model)

Dams:

- Okanagan Lake Control Dam
- Skaha Lake Dam
- McIntyre Dam

Bridges:

- Hwy 97 North Bridge
- Penticton Footbridge
- KVR Abutments Bridge (no deck)
- Green Mountain Road Bridge
- West Green Avenue Bridge
- Hwy 97 South Bridge
- Hwy 97 McAlpine Bridge
- No 22 Road Bridge
- Oliver Siphon
- Oliver Footbridge

The WaterSmith report and hydraulic model did not contain culvert information. Therefore, culvert data for the Okanagan Lake Regulation System (OLRS) was obtained from the recent Comprehensive Engineering Assessment of the OLRS Drainage Works (Ecora, 2019a). The report provided an up-to-date assessment of all the drainage structures in the OLRS system. The inspections were completed between March 6 and 12, 2018 and, where access was available, included pictures, and surveying of the structure inlet and outlet.

Based on the assessment report there are 68 structures throughout the whole system (with a total of 72 culverts since some structures have more than one culvert). These culverts are located in the dikes and allow the transfer of water between the floodplain and the channel. Culverts with flood gates are assumed to be operational and therefore closed during a flood event and were not be included in the model.

Of the 72 culverts, 39 do not have flood gates and of those 39, only 14 have complete survey information. Only structures with complete survey information are able to be included in the model. Some additional structures without survey information but with culvert sizing were able to be located with orthoimagery and Google Earth model. Therefore 20 culverts without flood gates and with survey information were included.

Lake Bathymetry

The lake bathymetry for much of the study area was provided by OBWB. Historic lake bathymetry was originally compiled for a study completed by DHI Water and Environment (2010). DHI digitized and merged the historic bathymetry data with a topographic DEM to derive overbank elevations. The DEM has a 20 m resolution.

Due to the coarseness of the DHI DEM, some necessary features in the lakes were lost. Therefore, Vaseux Lake, Skaha Lake, and Osoyoos Lake were all digitized using bathymetry maps from BC Ministry of Environment – Environmental and Engineer Service Water Investigations Branch – Storage Inventory Programme – Bathymetric Surveys of Skaha (surveyed in 1979), Vaseux (surveyed in 1976), and Osoyoos Lake (surveyed in 1981). The lake bathymetry was converted to the CVGD2013 datum after it was digitized.

The remaining bathymetry was utilized from the DHI DEM for Okanagan Lake, and Kalamalka/Wood Lake (all surveyed in 1994) which were originally obtained from Canadian Hydrographic Services (Fisheries and Oceans Canada, 2019).

Ellison/Duck Lake was not included in this bathymetry file and was digitized from the data catalog of bathymetric maps of surveyed lakes completed in 1971 (Ministry of Environment and Climate Change Strategy, n.d.).

Lidar

2015 Lidar

2015 lidar obtained from the Washington Department of Natural Resources was used to provide supplemental topographic data south of the Canada-United States border.

2018 Lidar

A digital elevation model (DEM) of the floodplain, derived from 2018 Lidar data, was received from OBWB and was used as the main source of overbank topography for hydraulic modelling and mapping purposes. The DEM has a 1.0 m resolution and was generated from Lidar data flown by Eagle Mapping Services Ltd. (Eagle Mapping) between March 2018 and November 2018. The Lidar data extend over the Okanagan basin from the northern limit of Okanagan lake down to Osoyoos Lake.

The 2018 Lidar data has a calculated vertical root mean square error (RMSE) of 0.074 m; this value was determined by Eagle Mapping by comparing the Lidar data to control points and features. The 2018 Lidar bare earth point cloud includes only the ground elevation data.

Horizontal coordinates of the 2018 Lidar data are in UTM Zone 11, NAD83. Vertical coordinates are based on CGVD2013.

2017 Lidar

The 2017 Lidar was flown by the National Disaster Mitigation Program (NDMP) between May 29, 2017 and June 6, 2017. The Lidar covers the Okanagan basin from the northern limit of Okanagan Lake to the 49th parallel, including Kalamalka Lake and the Coldstream Creek basin to Lumby.

The Lidar was flown during the peak of the 2017 flood event and was used to extract a water surface profile and flood extents for hydraulic model calibration. The calculated horizontal root mean square (RMSE) is 0.35 m and vertical RMSE is 0.10 m; these values were determined by GeoBC by comparing the Lidar data to horizontal control points and features. The 2017 Lidar bare earth point cloud includes only the ground elevation data.

Horizontal coordinates of the 2017 Lidar data are in UTM Zone 11, NAD83. Vertical coordinates are based on the CGVD2013.

Orthoimagery

Colour orthoimagery was flown during the same period as the 2018 Lidar and provided by GeoBC. The 2018 orthoimagery coverage was not complete across the valley due to smoke from wildfires.

2017 colour orthoimagery was collected between May 29, 2017 and June 6, 2017 by NDMP during the freshet flood in the Okanagan Basin. The 2017 orthoimagery was used to interpret flooded features on the floodplain and to help establish flood extents and HWMs in conjunction with the 2017 Lidar.

The 2018 imagery was used to classify land use for the hydraulic modelling of the valley. Any gaps in the 2018 orthoimagery coverage were filled in with the 2017 orthoimagery.

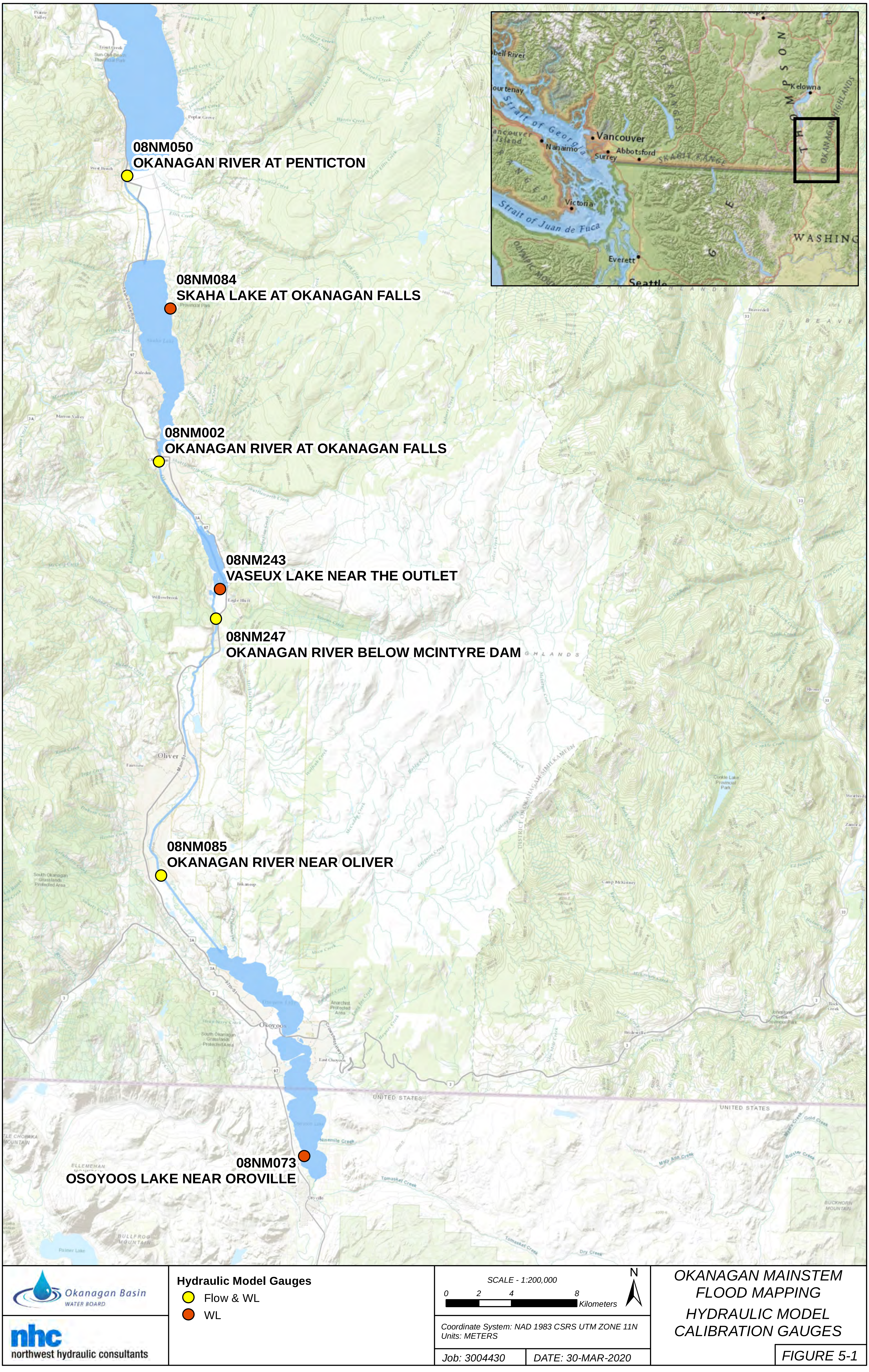
Hydrometric Data

Hydrometric data are described in detail under the hydrology section of this report. WSC and USGS operate several gauges within the study reaches. Those used in hydraulic model calibration are listed in Table 5-1 and shown in Figure 5-1.

Table 5-1 WSC and USGS gauge summary for hydraulic modelling.

ID	Name	Record Length
08NM050	Okanagan River at Penticton	2011-2018
08NM084	Skaha Lake at Okanagan Falls	1943-2018
08NM002	Okanagan River at Okanagan Falls	2011-2018
08NM243	Vaseux Lake near the Outlet	1991-2018
08NM247	Okanagan River below McIntyre Dam	2012-2018
08NM085	Okanagan River near Oliver	2011-2018
08NM073 (USGS 12439000)	WSC Osoyoos Lake near Oroville	1928-2017

The water level and discharge records for these gauges were obtained from WSC and/or USGS. Some of the gauges had elevations reported in a local datum. The elevations were converted to CGVD2013 using the benchmark data surveyed by WSP in 2019.


08NM050
OKANAGAN RIVER AT PENTICTON
08NM084
SKAHA LAKE AT OKANAGAN FALLS
08NM002
OKANAGAN RIVER AT OKANAGAN FALLS
08NM243
VASEUX LAKE NEAR THE OUTLET
08NM247
OKANAGAN RIVER BELOW MCINTYRE DAM
08NM085
OKANAGAN RIVER NEAR OLIVER
08NM073
OSOYOOS LAKE NEAR OROVILLE
Kelowna
Vancouver
Nanaimo
Surrey
Abbotsford
Victoria
Everett
Seattle
Strait of Georgia
Strait of Juan de Fuca
Oliver
Osoyoos
UNITED STATES
Okanagan Basin WATER BOARD
nhc northwest hydraulic consultants
Hydraulic Model Gauges
Flow & WL
WL
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0 2 4 8 Kilometers
N
Coordinate System: NAD 1983 CSRS UTM ZONE 11N
Units: METERS
Job: 3004430
DATE: 30-MAR-2020
OKANAGAN MAINSTEM FLOOD MAPPING
HYDRAULIC MODEL CALIBRATION GAUGES
FIGURE 5-1

High Water Marks

A large flood occurred in the Okanagan Basin in the spring of 2017. HWM were extracted based on the water surface elevation and flood extents in the 2017 Lidar flown during the peak of the flood event. The HWM's were used for hydraulic model calibration.

5.3 River Model Development

HEC-RAS, a computer program developed by USACE's Hydrologic Engineering Center (HEC), was used to simulate the flood conditions and calculate the flood profile. Version 5.0.7 was released in March of 2018 and was used for this study. The program is designed to perform one-dimensional (1D), two-dimensional (2D), or combined 1D and 2D hydraulic calculations for a full network of channels. The model includes a number of routines for simulation of various hydraulic structures, such as bridges, culverts, weirs, dikes, and spillways. For this project, a 1D-2D coupled unsteady flow model was used to determine the flood extents for the Okanagan Basin, with 1D used in the main channel and 2D for the floodplain areas behind the dikes. Model simulations were conducted using the full momentum St. Venant equations in both the 1D and 2D areas.

Unlike standard 2D models, the 2D computational cells used in HEC-RAS do not have a single averaged elevation. Instead, each cell and cell face of the computation mesh is pre-processed in order to develop detailed hydraulic property tables based on the underlying terrain. This allows a large cell (e.g. 50 m x 50 m) to be partially wet with the correct water volume based on the modelled water surface elevation and the digital elevation model resolution (e.g. 1 m x 1 m).

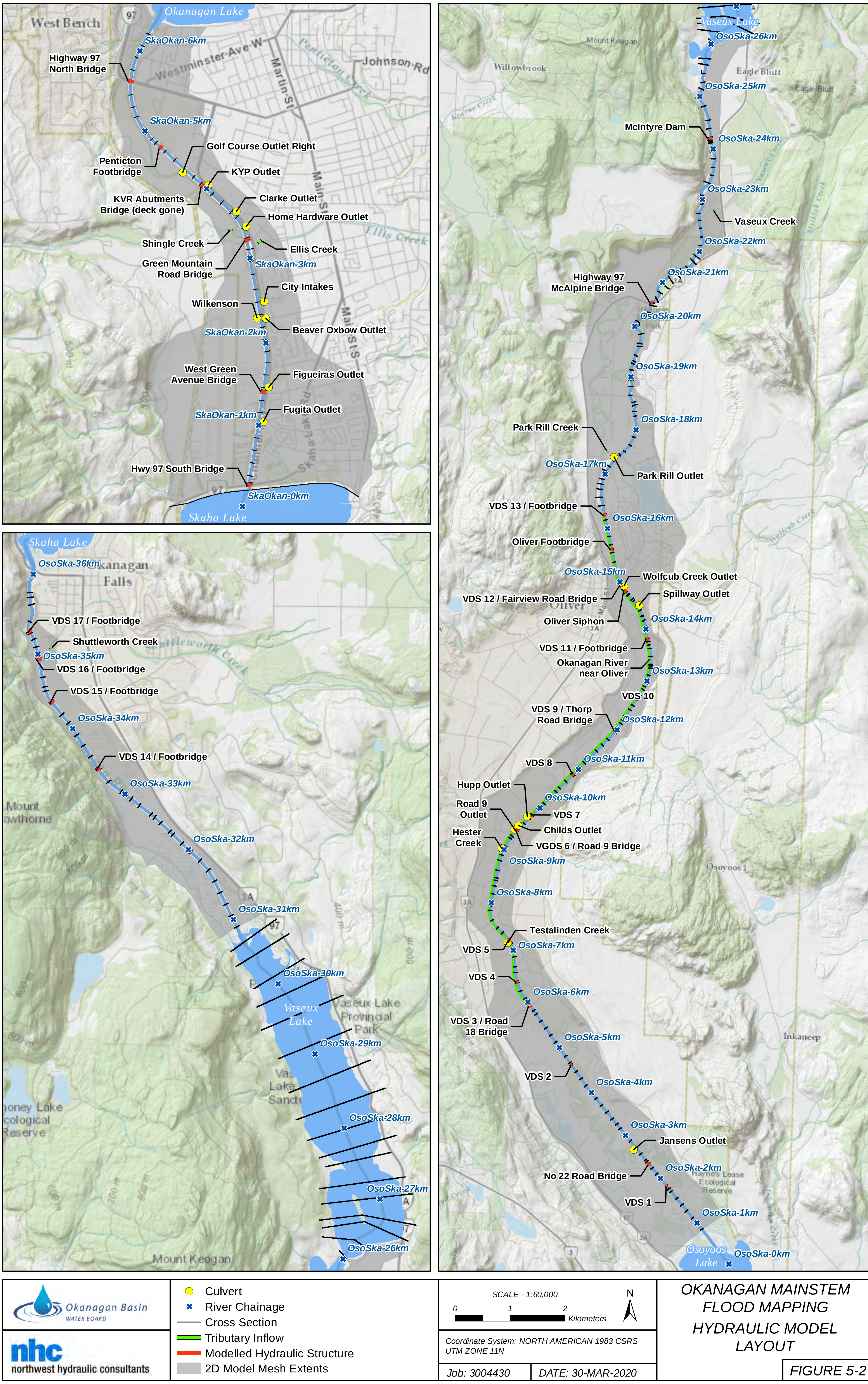
DEM Development

A DEM was generated by combining a one-metre horizontal resolution bare earth DEM based on the 2018 Lidar with the lake bathymetry. 2015 Lidar obtained from the Washington Department of Natural Resources was used to provide supplemental topographic data south of the Canada-United States border. The lake bathymetry and the US 2015 Lidar were converted to UTM Zone 11 NAD83 CSRS metres, CGVD2013 before merging the data. The final DEM has a one-metre horizontal resolution.

Where cross sections were needed in the hydraulic model, the DEM was combined with the surveyed cross section data. The DEM was used as is to represent the overbank areas in the hydraulic model.

Geometry Development

Two separate models were developed for the study area. The upstream model covers the river and floodplain between Okanagan and Skaha lakes. The downstream model begins immediately downstream of Skaha Lake and extends to Osoyoos Lake. Okanagan, Skaha and Osoyoos lakes are not represented in the model, but Vaseux Lake is Figure 5-2.



Okanagan Basin WATER BOARD

nhc northwest hydraulic consultants

Coordinate System: NORTH AMERICAN 1983 CSRS UTM ZONE 11N

Job: 3004430 DATE: 30-MAR-2020

OKANAGAN MAINSTEM FLOOD MAPPING

HYDRAULIC MODEL LAYOUT

FIGURE 5-2

\\mainfile-van\Projects\Active\3004430 Okanagan Flood Map\95 GIS\3004430_MAO_ModelOverviewLayout_r0a.mxd

The 1D portion of the models includes the main river channel and Vaseux Lake and contains all the existing hydraulic structures affecting in-channel flows. The channels/lake are represented by a series of cross-sections surveyed by WSP Global in 2019. The dimensions of the existing hydraulic structures were obtained from the WaterSmith and Streamworks report and model (2014). The total channel and lake length is approximately 60 km.

The 2D portion of the models was developed for the floodplain areas using available Lidar data. The 2D grid cell size was established from preliminary test simulations to provide sufficient resolution of the topographic details and simulated hydrodynamic data while maintaining manageable model run times. The 1D and 2D models are linked via dikes and culverts to provide flow exchange between the channels/lake and floodplain areas during high flow events.

The bathymetric profile for the whole reach including the lakes is shown in Figure 5-3. The figure shows the river stationing in profile as well as location of hydraulic structures included and not included in the model to provide a frame of reference. Table 5-2, Table 5-3 and Table 5-4 list the hydraulic structures used in the modelling and their stationing.

Table 5-2 Summary of bridges included in hydraulic model.

Description	Reach	River Station (m)	Details
No 22 Road Bridge	Osoyoos to Skaha	2,326	45 m long, 1 pier, low chord elevation of 281.0 m, high chord elevation of 281.9 m
Oliver Siphon	Osoyoos to Skaha	14,819	39 m long, 3 piers, skewed crossing, low chord elevation of 296.5 m, high chord elevation of 298.63 m
Oliver Footbridge	Osoyoos to Skaha	15,606	37 m long clear span, low chord elevation of 298.5 m, high chord elevation of 299.9 m
Hwy 97 McAlpine Bridge	Osoyoos to Skaha	20,535	33 m long clear span, low chord elevation of 309.2 m and high chord elevation 310.5 m
Hwy 97 South Bridge	Skaha to Okanagan	284	45 m long, 3 piers, low chord elevation of 340.3 m, high chord elevation of 341.4 m
West Green Avenue Bridge	Skaha to Okanagan	1,395	40 m long, 2 pier, low chord elevation of 339.9 m, high chord elevation of 341.2 m
Green Mountain Road Bridge	Skaha to Okanagan	3,213	47 m long, 3 piers, low chord elevation of 342.7 m, high chord elevation of 343.74 m
KVR Abutments Bridge (no deck)	Skaha to Okanagan	4,051	Abutments only, no deck.
Penticton Footbridge	Skaha to Okanagan	4,730	36 m long clear span, low chord of 342.41 m, high chord of 343.9 m
Hwy 97 North Bridge	Skaha to Okanagan	5,623	48 m long, 3 piers, low chord elevation of 343.1m, high chord elevation of 344.1 m

Table 5-3 Summary of vertical drop structures included in hydraulic model.

Description	Reach	River Station (m)
VDS 17	Osoyoos to Skaha	35,286
VDS 16	Osoyoos to Skaha	34,934
VDS 15	Osoyoos to Skaha	34,402
VDS 14	Osoyoos to Skaha	33,435
VDS 13	Osoyoos to Skaha	16,248
VDS 12 - Fairview Road	Osoyoos to Skaha	14,928
VDS 11	Osoyoos to Skaha	13,815
VDS 10	Osoyoos to Skaha	12,747
VDS 9 - Thorp Road	Osoyoos to Skaha	11,952
VDS 8	Osoyoos to Skaha	10,858
VDS 7	Osoyoos to Skaha	9,803
VDS 6 - Road 9	Osoyoos to Skaha	9,419
VDS 5	Osoyoos to Skaha	7,197
VDS 4	Osoyoos to Skaha	6,418
VDS 3 - Road 18	Osoyoos to Skaha	5,932
VDS 2	Osoyoos to Skaha	4,605
VDS 1	Osoyoos to Skaha	1,795

Table 5-4 Summary of dams included in hydraulic model.

Description	Reach	River Station (m)	Details
McIntyre Dam	Osoyoos to Skaha	24,194	5 Gates

Flow between the river channel and floodplain is exchanged using lateral structures, a HEC-RAS model option most commonly used to represent dikes aligned parallel to the river channel. Dike alignments were digitized from the DEM and the crest elevations extracted to input into the lateral structures. In a few locations there is no true dike along the riverbanks, but the same procedure was used to delineate the top of bank elevations that control overbank flooding patterns. Bi-directional flow is allowed at lateral structures when water levels exceed dike crest elevations. Standard weir flow equations are used by the model to calculate flows overtopping the dikes. The coefficient of discharge was set for the lateral structures based on guidance from the HEC-RAS manual. Culverts without flood gates were also added to the lateral structures at the locations noted above.

Boundary Conditions

The upstream boundary conditions for the hydraulic model included an inflow just south of Okanagan Dam for the Skaha to Okanagan reach and an inflow just south of Okanagan Falls Dam for the Osoyoos to Skaha reach. The inflows for these locations were supplied by the output from the hydrology model discussed in Chapter 3.

The downstream boundaries for the model were stage boundaries set by the lakes. Skaha Lake level controlled the Skaha to Okanagan reach and Osoyoos Lake controlled the Osoyoos to Skaha reach. Only major tributaries to the river were included and the tributary inflows were set by the hydrology model. The tributaries included and their river station are presented in Table 5-5.

Table 5-5 Tributaries included in hydraulic model.

Tributaries	Boundary Type	River Station (m)
Ellis Creek	Point Source	3,000
Shingle Creek	Point Source	3,271
Shuttleworth Creek	Point Source	34,874
Vaseux Creek	Point Source	36,468
Park Rill	Point Source	17,343
Lateral Drainage near Oliver	Lateral Inflow	16,240

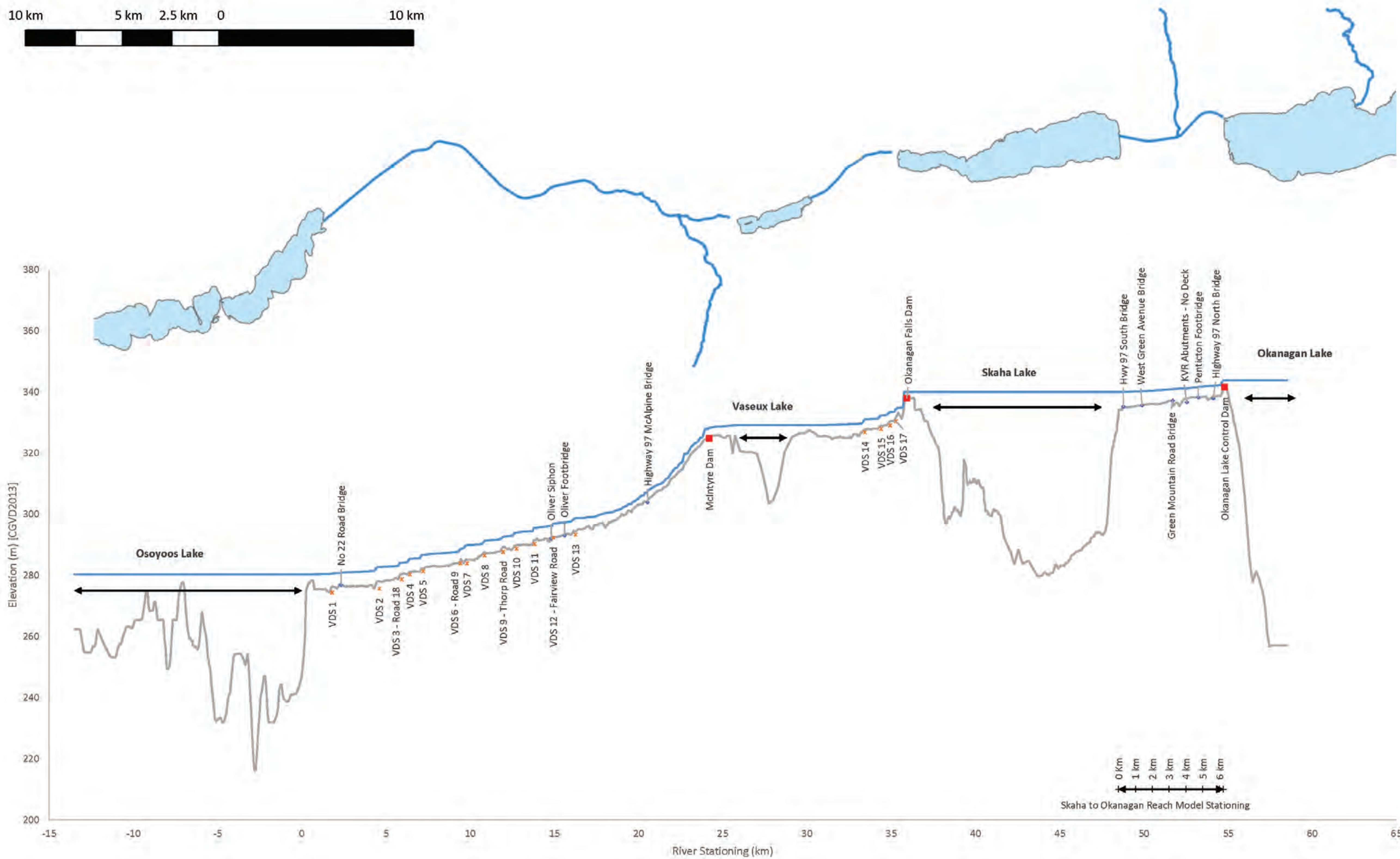


Figure 5-3 **Okanagan River Profile.**

5.4 Calibration and Validation

Roughness Coefficients

Within the 1D model, the calculated velocity and subsequent water surface profile is strongly dependent on the channel roughness. For a 1D model, the roughness factor accounts for friction losses resulting from surface roughness, vegetation, channel irregularities (variations in cross section size and shape), obstructions (stumps, roots, logs, isolated boulders), and channel alignment (degree of meandering). In a 2D model much of the friction losses (variations in channel shape and alignment) are accounted for in the momentum equation and consequently Manning's n-values in the 2D areas are generally lower.

The Okanagan River was divided into sub-reaches with similar channel bed material, sectional geometry, and plan form. Each sub-reach was then assigned a roughness value for the in-channel portion of the cross section. Initial roughness values were assigned based on values used in previous hydraulic models of the Okanagan River (WaterSmith Research Inc & Streamworks Consulting Inc, 2014) and verified with values referenced in the literature (Barnes, 1967; Brunner, 2016; Chow, 1959; Hicks and Mason, 1998). The roughness of the channel and overbank were specified in the model using Manning's n coefficients.

For the Okanagan River, a Manning's n coefficient of 0.029 was used for in-channel roughness. The overbank portion of the cross sections were assigned roughness values based on land use identified in the aerial imagery. The following overbank land use categories were used and were assigned Manning's n roughness values ranging from 0.024 to 0.1:

- Side channel,
- Grass (cultivated areas or pasture),
- Light brush or shrubs,
- Trees (heavy stand of timber but with dense undergrowth, and flow into branches),
- Lake or ponded water, and
- Urban development.

2017 Calibration

To best support model calibration or validation, HWMs should have been established at a known flood flow (such as the peak of a flood event), surveyed at or shortly after the event, and be recent enough to represent current channel and floodplain conditions. The Okanagan Basin experience a recent flood event in June 2017 where Lidar was flown during the highwater event allowing a large cache of potential HWMs to be captured.

The model was calibrated to that June 2017 flood event, with flows that reached the maximum output regulations allowed for Okanagan Dam during an emergency (78 m^3/s). Model boundary conditions for the calibration were based on the observed flows at WSC gauges listed in Table 5-1. The gauges that were not used to provide boundary conditions were used as calibration points (08NM243 – Vaseux lake near the outlet, 08NM247 – Okanagan River Below McIntyre, and 08NM085 – Okanagan River near

Oliver). More weight was attributed to the calibration values from the gauges than those provided by the Lidar. The Lidar calibration points were pulled using an average through all the points collected in a profile from the water surface. The scatter in the Lidar points covered a range of about 0.3 m.

A comparison of 2017 observed and final simulated water surface elevations (WSEs) is plotted in Figure 5-4 and Figure 5-5. As shown in the figure, the model somewhat over-predicts water levels. The mean absolute error (MAE) between observed Lidar WSEs and simulated water levels for the Skaha Lake to Okanagan Lake reach is 0.11 m and for the Osoyoos Lake to Skaha Lake reach is 0.23 m. The MAE for the observations pulled from the WSC gauges in the Osoyoos Lake to Skaha Lake reach is 0.05 m.

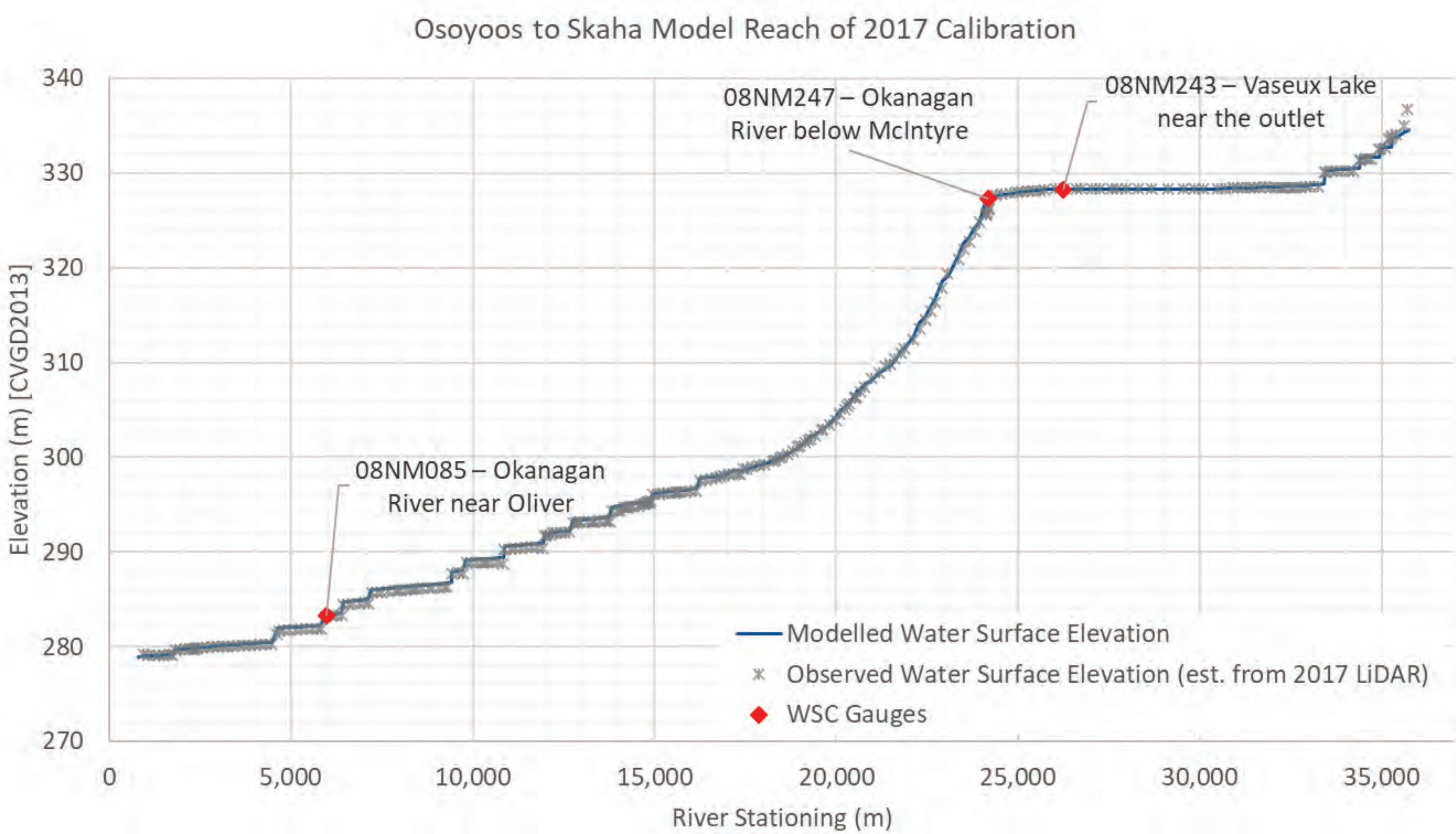


Figure 5-4 2017 calibration profile plot of Osoyoos Lake to Skaha Lake reach of Okanagan River.

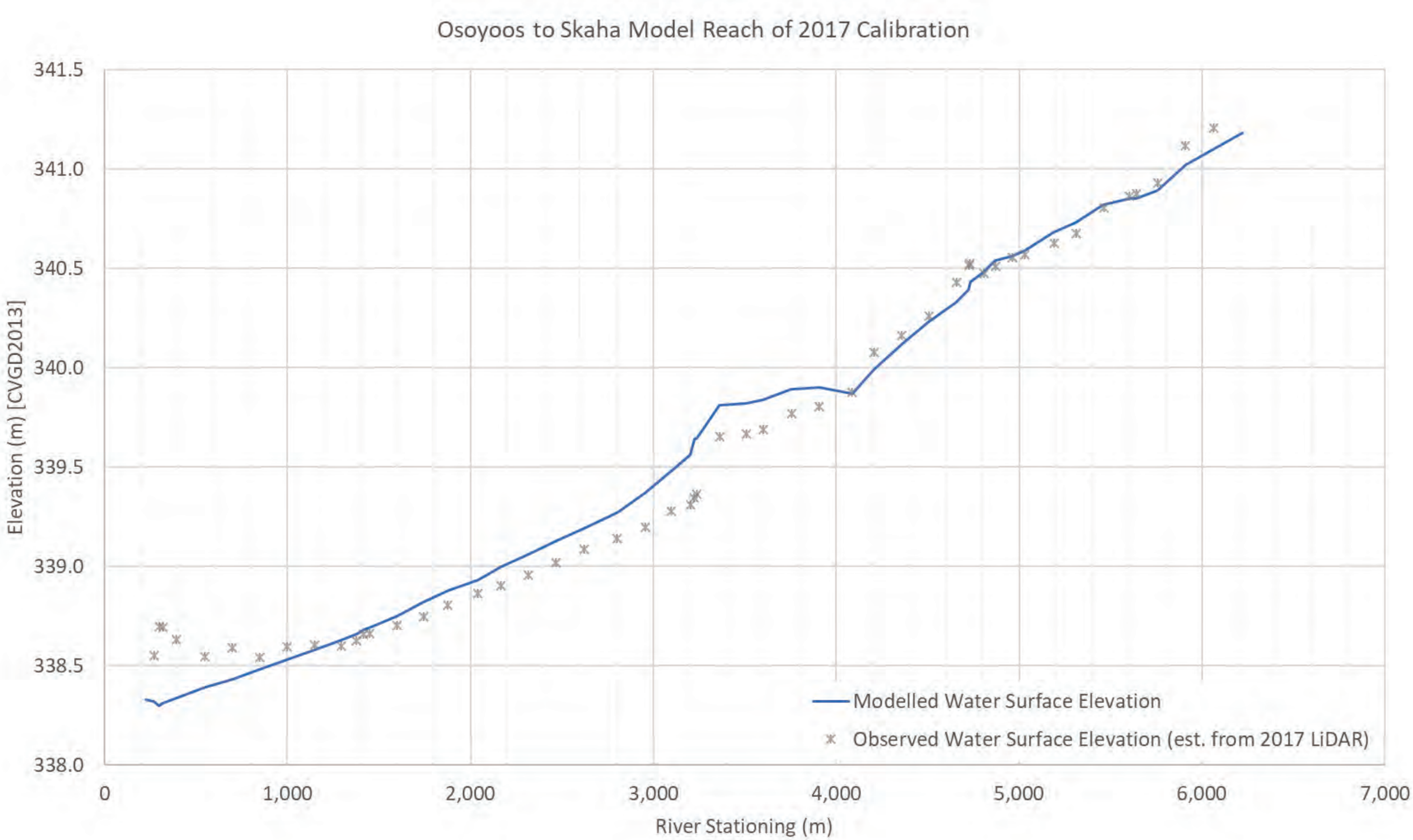


Figure 5-5 2017 calibration profile plot of Skaha Lake to Okanagan Lake reach of Okanagan River.

The difference between 2017 HWMs and simulated peak water levels is attributable to:

- Uncertainty in the Lidar points. It is not clear the extent of the Lidar's ability to pick up WSE from the rivers surface and under what conditions these may be inaccurate. There is also uncertainty in the collection time of the Lidar points. It was narrowed down to several days when the Lidar was flown, but several passes of the same body of water can show different levels if the flights were on different days. The HWMs therefore may not accurately reflect the highest water levels experienced during the 2017 flood.

Despite the comparison with the Lidar data suggesting that the model over-predicts the 2017 water level, channel roughness values were not further adjusted for the following reasons:

- The roughness values selected are at the low end of plausible values for the channel form, bed texture, and channel slope based on referenced literature and past modelling experience.
- The model shows good agreement with the WSC gauges which provides more reliable data than the Lidar.

2018 Validation

The flood event in late May / early June 2018 (66 m^3/s at Okanagan Lake outlet) was used as a validation event, which is to confirm the calibrated model appropriately represents flow conditions other than just the calibrated event. The 2018 event was not quite as high as the 2017 event and did not have HWMs other than from available gauge data. Since there are no gauges between 08NM050 – Okanagan River at Penticton and the inlet to Skaha Lake, there was no validation that was able to be completed through this upper reach.

Only the three gauges described above were able to be used as validation points for model from Osoyoos to Skaha. Since the river and the lakes all peak at separate times, the model was run from May 5, 2018 – June 5, 2018 using the observed gauges as boundary conditions. The results of the 2018 validation are summarized in the table below.

Table 5-6 Differences in simulated WSE for 2018 validation event.

WSC Gauge	Mean Absolute Error (m)
08NM243 – Vaseux lake near the outlet	0.05
08NM247 – Okanagan River Below McIntyre	0.15
08NM085 – Okanagan River near Oliver	0.09

5.5 Results

In BC, floodplain mapping is typically developed for the 200-year ARI flood or the flood of record if greater. For the Okanagan River, the 200-year mid-century climate change scenario with gates open was selected as the design flood event for floodplain mapping. The 20-year mid-century, 100-year mid-century and 500-year end of century floods were also modelled. Inflow to the model was set at the upstream end of the model as well as at each tributary as defined in the following subsection on boundary conditions. The tributaries for the Okanagan River, however, were not modelled except where controlled by backwater elevations from the river. The profile plot of the 200-year mid-century design flood can be seen in Figure 5-6 and Figure 5-7.

Boundary Conditions

To simulate the selected design floods, the boundary conditions specified in Table 5-7, Table 5-8, and Table 5-9 were used. See section 3.5 for recommended flow estimates of ARI events. Results from the hydrology model were used to define the simulation flows for the hydraulic model. These results were limited to the upstream and downstream end of each reach. The increase in flow along the reach was accounted for in the hydraulic model by incorporating inflow at the major tributaries (Table 5-9). The amount of flow assigned to each tributary was scaled based on the weighted average of each tributary's mean annual flood, as obtained from the hydrologic model.

Table 5-7 Flood flow estimates used in hydraulic model.

ARI	Flow Estimate at Outlet of Okanagan Lake (m^3/s)	Flow Estimate at Outlet of Skaha Lake (m^3/s)
20-year mid-century	119	131
100-year mid-century	140	152
200-year mid-century (Design Event)	153	168
500-year end of century	176	194

Table 5-8 Flood lake level estimates for the used in hydraulic model.

Lake	ARI Lake Level Estimate (m, CVGD 2013)			
	20-year mid-century	100-year mid-century	200-year mid-century (Design Event)	500-year end of century
Skaha Lake	339.37	339.98	339.72	340.38
Osoyoos Lake	279.52	280.36	280.07	280.99

Table 5-9 Tributary inflows estimates used in hydraulic model.

Tributaries	Tributary Inflow (m^3/s)			
	20-year mid-century	100-year mid-century	200-year mid-century (Design Event)	500-year end of century
Ellis Creek	8.3	8.8	10.7	11.4
Shingle Creek	6.2	6.5	8.0	8.5
Shuttleworth Creek	2.5	2.8	3.2	4.6
Vaseux Creek	16.0	17.4	19.7	31.4
Park Rill	1.4	1.5	1.7	2.8
Okanagan River near Oliver	0.7	0.8	0.9	1.4

Model Geometry

The model geometry used for calibration and validation simulations was unaltered for the design simulations and was assumed to be representative for all the flood events. No allowance for bed scour or localized deposition was introduced. Similarly, no debris blockages or avulsions were considered. Dikes were assumed to maintain their elevation as currently surveyed even if overtopped. Model development, calibration, and validation is based on large flood events. The floodplain drainage network, including culverts landward, beyond the dikes, and canals or ditches outside of the main river, was not modelled in detail. Hence, the model may not provide accurate representation of low to moderate flow events.

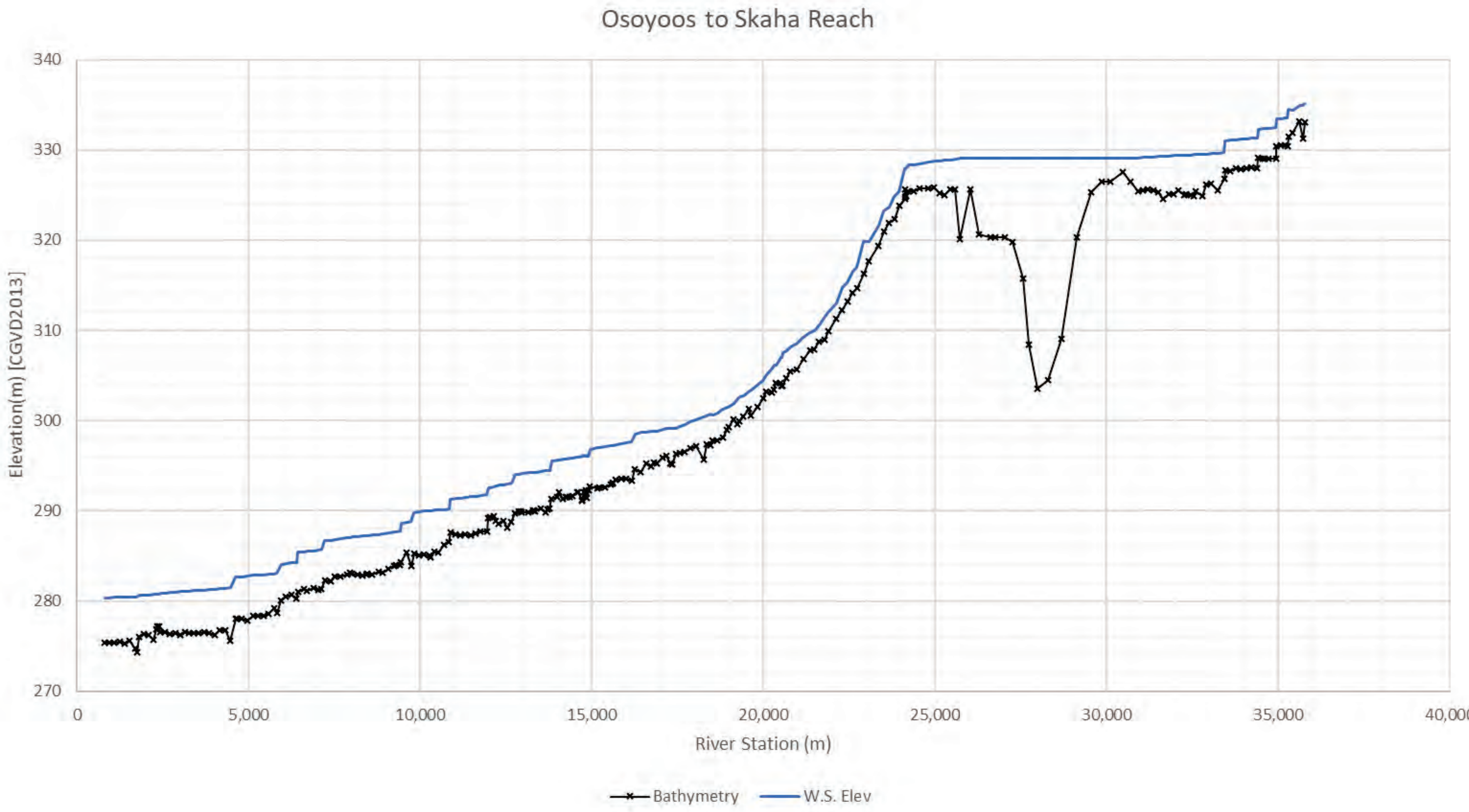


Figure 5-6 Water level profile of the 200-year mid-century design flood for the Osoyoos Lake to Skaha Lake reach of the Okanagan River.

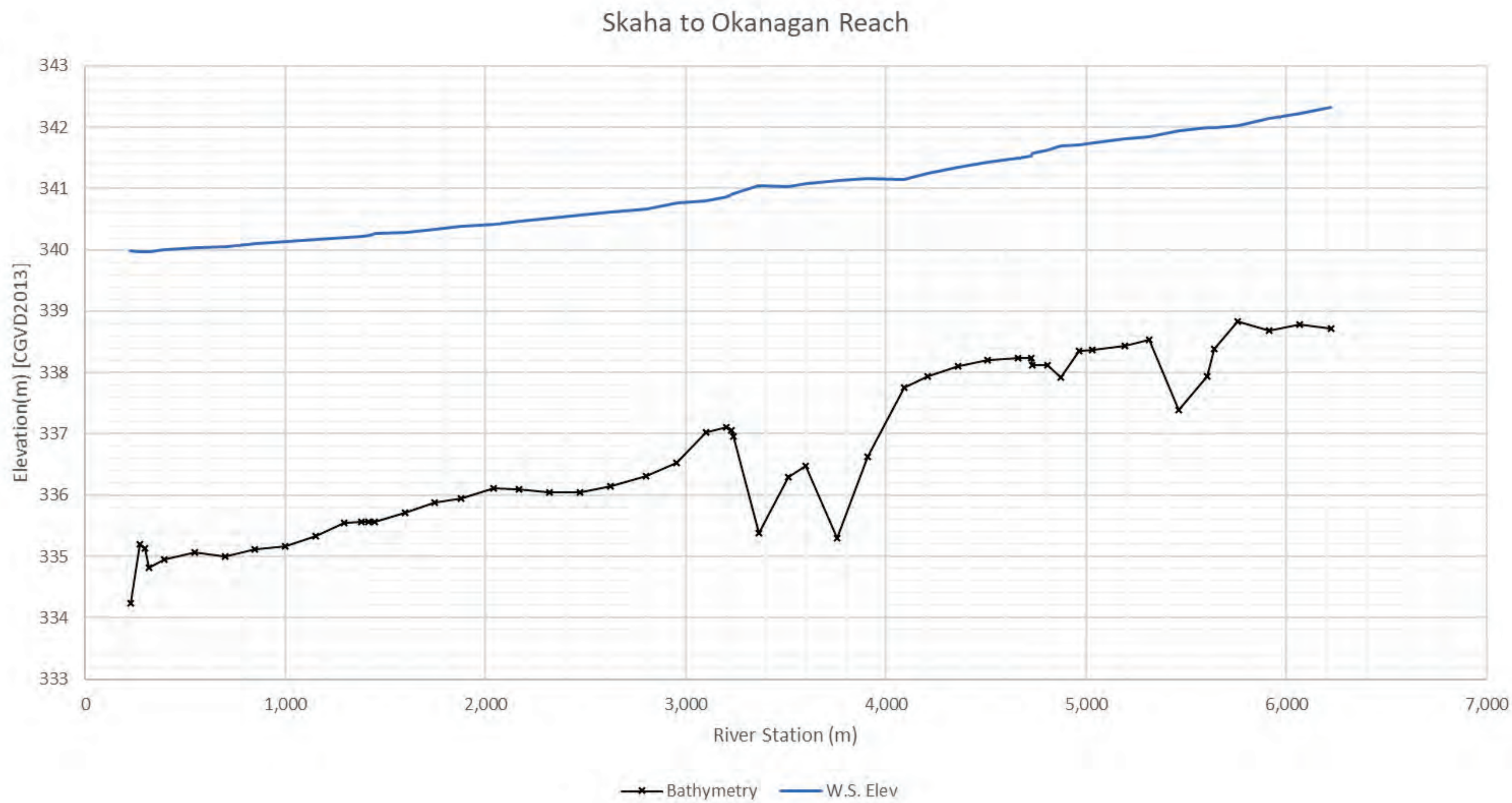


Figure 5-7 Water level profile of the 200-year mid-century design flood for the Skaha Lake to Okanagan Lake reach of the Okanagan River.

Model Sensitivity

The simulated model results (i.e. the flood level) are primarily dependent on the channel geometry and flow. Other model parameters can however also influence the results, such as:

- Boundary conditions (upstream inflow and downstream water levels),
- Channel roughness values,
- Overbank roughness values, and
- Topographic uncertainties.

Values for these parameters were varied within a reasonable range and simulations of the flood flows repeated. The resulting water level profile was compared with the design water level profile to determine the effect of potential error in each parameter on the model results. Results from the sensitivity analysis confirmed that the water profile within the study boundary would not be impacted by reasonable changes in the downstream boundary conditions and that potential misrepresentation of channel and overbank roughness would typically result in changes in design water level of less than or equal to 0.1 m and no more than 0.3 m. This magnitude of potential error is considered reasonable and is within typically applied freeboards to account for such potential errors.

5.5.1 Model and Data Uncertainties

The basic assumptions and limitations of the HEC-RAS model include:

- The channel bed and banks are fixed (the actual river is subject to scour and deposition during floods).
- A uniform hydrostatic pressure distribution is assumed across the channel sections resulting in a level water surface from one bank to the other (i.e. ignoring local variations in water level across the channel from local bed variations or superelevation around corners).

Additional uncertainties in available data:

- Uncertainties in survey data (0.10-0.15 m for topographic data and 0.05 m for gauge station data).
- Uncertainty in the Lidar data; see section 5.4 for Lidar error estimates.
- Although specified to contain bare-earth data, the Lidar used for developing the DEM may contain some artificially high points, especially in areas where the vegetation is dense, creating unrealistic “dry spots” for some floodplain model runs. Additionally, the DEM may contain low points or under predict the crest height on structures that are porous by natures (large rock constructs such as breakwaters or riprap structures).
- Some bathymetric gaps exist between where the lake bathymetry ends, and the river bathymetry starts. There is about 350 m of river above Okanagan Falls that is not in the hydraulic river model and not covered in the lake bathymetry.

- Hydraulic structures surveyed by WaterSmith Resource Inc. and Streamworks Consulting Inc. (2014) are assumed to be accurate representations of the hydraulic structures in the Okanagan River. This includes the vertical drop structures and the dams where applicable.
- Culverts, ditches/canals and other drainage features were not specifically modelled on the floodplain.
- Only culverts in the dikes of the OLRS without flap gates and with survey data as identified in the Comprehensive Engineering Assessment of the OLRS Drainage Works by Ecora (2019a) were included in modelling. This assumes culverts with flap gates are functioning fully and in good condition. Culverts are assumed to be free of debris and flowing smoothly.
- WSC flow and stage data for 2018 used in this study was classified as preliminary by WSC (therefore it is subject to change). The final data is not available at the time of this report and as such, the values were not updated beyond what was provided in the preliminary data.

5.6 Conclusions, Recommendations, and Future Work

Based on the available Lidar and channel survey, a 1D-2D coupled quasi-steady flow model was developed. The model was calibrated to the June 2017 flood (78 m^3/s) and further validated with the May 2018 flood (66 m^3/s). Sensitivity analysis was then conducted using the design flood event for a plausible range of model parameters. A design flood profile was generated from the model for the 200-year ARI (open gates) mid-century design flood as well as the 20-, 100-, and 500-year ARI mid-century (open gates) floods. A freeboard of 0.6 m is recommended for definition of design values, such as the FCL, to account for the level of uncertainty in the calculated water level indicated by the calibration, validation, and sensitivity analysis.

A formal comparison of the design water level profile to dike crest elevations is not part of the current scope of work. However, the dikes appear to be adequately high for much of the river to contain the design flood.

Recommended future work includes:

- Conduct a formal assessment of the dikes and flood mitigation measures to ensure they are adequate to withstand the newly developed design flood profile. Such an assessment should include survey of the dike but may also include visual inspection of dike condition and geotechnical evaluation.

▪ The current rating curves are limited to a single open gate scenario, for the structures at the outlet of Kalamalka Lake, Okanagan Lake (Penticton Dam), Skaha Lake (Okanagan Falls Dam), and Vaseux Lakes (McIntyre Dam). While total outflow is currently monitored with the use of near real-time discharge data from downstream gauges, this does not allow for such well-informed operations in the case of an outage (with the real-time data unavailable) potentially needed during an emergency. The real-time gauge data is also reliant on rating curves specifically developed for the river, which may shift and are preliminary until reviewed and published, so the discharge data reported by the gauge is uncertain during operation.

  Rating curves developed for the dams can be refined for complete operation dependent on water level and gate opening using numerical methods, computational fluid dynamics (CFD), and physical modelling. Although CFD modelling is often suitable for freeboarding condition, the level of accuracy decreases to 20% or worse when flow reaches the gate. Field measurements can be used to help calibrate and validate the assessment, however often it is challenging to operate at the most extreme values, which generally are of the most interest. Physical modelling of gates is therefore used for the most detailed development of gate rating curves.

Inset 5-1 Example of a custom gate physical model, NHC-Vancouver Hydraulics Laboratory.

▪ HWMs should be collected during all high flow events. This information is useful for model calibration and validation which should be done following any large flood event. The HWM's should be taken along the entire profile of the modelled reach with sufficient spacing to capture any substantial breaks in slope (i.e. such as upstream and downstream of all hydraulic structures and any constrictions or change in slope). The HWM's should be collected at the same flow, ideally near the peak of the flood event. The HWM can be staked during the flood and surveyed after it recedes as long as the duration is not so long following the flood that the HWMs may be damaged or moved.

CHAPTER 6 FLOODPLAIN MAPPING & APPLICATIONS

6.1 Chapter Synopsis

Okanagan Valley lake and riverine floodplain maps were derived from the river and lake modelling described in previous chapters. Floodplain maps have been prepared that include flood inundation level and extent for mid-century flood events, riverine velocity and depth, as well as design FCLs that incorporate freeboard. These maps have been provided as GIS layers (Table 6-2) as well the FCL maps that accompany this report. The maps have been compared to previous Okanagan Valley flood mapping.

The goal of floodplain mapping is to reduce the risk of floods through improving understanding of the hazard and allowing First Nations, governments, organizations and individuals to plan for potential floods and reduce their risk. Flood risk reduction approaches are summarized in section 6.5, including structural mitigation and non-structural. As part of the educational component of non-structural mitigation, an interactive and informative online website was developed to provide public access to flood hazard information.

Following the development of a sophisticated understanding of the flood hazard in the Okanagan region gained through this project, First Nations, governments, and residents have an opportunity to further develop their comprehensive flood mitigation strategies.

6.1.1 Limitations on Floodplain Mapping Component of this Study

- The design flow magnitudes are projected to increase over time as a result of climate change. The design flood events applied for the lake and riverine reaches are based on a modified operational regime of the flow control structures at the outlet of the lakes. If the operational regimes of these structures are not modified to adapt to the increasing flow regime, then flood levels and extents will be greater than those illustrated in the maps.
- The maps delineate FCL extents under the design flood event. Mapping of the Okanagan River, Skaha Lake, Vaseux Lake, Ellison Lake, and Osoyoos Lake is based on the 200-year mid-century (2041-2070) design event. Mapping of Okanagan Lake and Wood / Kalamalka lakes is based on the flood of record (2017) adjusted to mid-century for climate change. Tributaries are not included in mapping.
- The mapped FCL includes a freeboard allowance of 0.6 metres, which has been added to the calculated flood water level to account for local variations in water level and uncertainty in the design event estimates. The inundation maps do not include freeboard, and hence should only be considered with an understanding of the uncertainty in their results.
- The FCLs shown on all lake maps include an allowance for wind setup (except Ellison) and wave runup based on co-occurrence of the seasonal 200-year wind event. The wind and wave effects extend 40 m shoreward to delineate the expected limit of wave effects. Beyond this limit the FCL is based on inundation of the flood event without wave effects. Shorelines FCLs take precedence over lake inundation FCLs. Wave effects have been calculated based on generalized shoreline profile and roughness for each shoreline reach. Site specific runup analysis by a Qualified Professional may be warranted to refine the generalized wave effects should the shoreline slope be significantly different than the

generalized profile used for that reach (Table 4-7). Site-specific analysis could increase or decrease the FCL by as much as a metre.

- Underlying hydraulic analysis assumes channel and shoreline geometry is stationary. Erosion, deposition, degradation, aggradation, and local blockages may occur during a flood event to sufficiently alter actual observed flood levels and extents. Obstructions, such as log-jams, local storm water inflows or other land drainage, groundwater, or tributary flows may cause flood levels to exceed those indicated on the maps.

- The Okanagan floodplain is subject to persistent ponding due to poor drainage. Persistent ponding is not covered by the flood inundation mapping.

- The majority of the Okanagan River is diked; breaching of the dike was not modelled. Isolated areas below the FCL (as projected perpendicular to flow from the channel), such as those landward of the dikes, are mapped as inundated. This delineation accounts for potential failure and breaching of the dike, seepage through, or inflows trapped behind the separating dike or embankment. This approach is consistent with BC floodplain mapping guidelines.

- Filtering was used to remove isolated areas smaller than 100 m^2. Holes in the inundation extent with areas less than 100 m^2 were also removed. Isolated areas larger than 100 m^2 were retained for mapping if they were within 40 metres of direct inundation or within 40 metres of other retained polygons.

- Okanagan Dam breach and dam overtopping were not modelled. On the right bank of the Okanagan River from the Okanagan Dam downstream to the Highway 97 bridge, inundation mapping is based on modelling of design lake level overflowing to the river downstream; along the left bank downstream of Okanagan Dam inundation mapping is based on river modelling, as Okanagan Lake level overtopping along the left bank is limited to a localized area adjacent to the dam. Overflow at this site was not simulated.

- The accuracy of the selected design floods is limited by the reliability and temporal and spatial extent of water level, flow, and climatic data, as well as the operations of the lake outflow structures. The accuracy of floodplain levels and extents is limited by the accuracy of the design flood flow, the hydraulic model, and the digital surface representation of local topography, which is bare-earth (no buildings or structures). Localized areas above or below the FCL maybe generalized by the inundation mapping. Therefore, floodplain maps should be considered an administrative tool that indicates flood elevations and floodplain boundaries for a designated flood. A Qualified Professional is to be consulted for site-specific engineering analysis.

- Industry best practices were followed to generate the floodplain maps. However, actual flood levels and extents may vary from those shown. Residual flood risk beyond that mapped exists for flood events more extreme than the design events. OBWB and NHC do not assume any liability for variations of flood levels and extents from that shown.

6.2 Floodplain Mapping

Floodplain mapping for the Okanagan Basin covers from Okanagan Lake to the US border including Wood-Kalamalka, Ellison, Skaha, Vaseux, and Osoyoos Lake as well as the Okanagan River from Okanagan Lake to Osoyoos Lake. The mapping was developed from: hydrologic routing of flow through the lakes, river hydraulic modelling, and lake wave modelling. The results from the calculated water surface profiles were mapped on 116 sheets at 1:5,000 scale (maps of the FCL are included with this report). The flood mapping is based on the design flood scenario and includes FCLs for the river and the lakes with freeboard added to the simulated water level, as discussed in the next subsection. The floodplain maps are accompanied by an index map which includes detailed map notes.

The floodplain maps are designed according to mapping standards presented in NHC (2020b).

6.2.1 Coordinate System and Datum

The following has been used for the Okanagan Valley flood mapping:

- Coordinate system: UTM Zone 11. Coordinates in metres.
- Horizontal datum: NAD 83 (CSRS).
- Vertical datum: Geodetic – CGVD2013.

The horizontal datum for BC is NAD83. For the most accurate positioning, the CSRS realization of NAD 83 is used.

CGVD2013 is a new vertical datum for Canada, gradually being adopted across the country.[1] The Province of BC is developing a transition plan and tools to support migration to CGVD2013.[2] CGVD2013 will replace the older CGVD28 HTv2.0_2002 vertical datum. Conversion between the two datums can be done with spot heights inputted into NRCan's online tool GPS-H[3], or through development of an in-house conversion grid.

Changes in the elevations between the two vertical datums for representative locations in the Okanagan Valley are shown below in Figure 6-1 and Table 6-1. Values were calculated using the NRCan GPS-H tool. Differences range from 0.190 m to 0.332 m.

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[1] Natural Resources Canada (2017). Height Reference System Modernization, https://www.nrcan.gc.ca/earth-sciences/geomatics/geodetic-reference-systems/9054

[2] Government of British Columbia. Vertical (Height) Reference System, https://www2.gov.bc.ca/gov/content/data/geographic-data-services/georeferencing/vertical-reference-system

[3] Natural Resources Canada (2019). GPS-H, http://webapp.geod.nrcan.gc.ca/geod/tools-outils/gpsh.php?locale=en

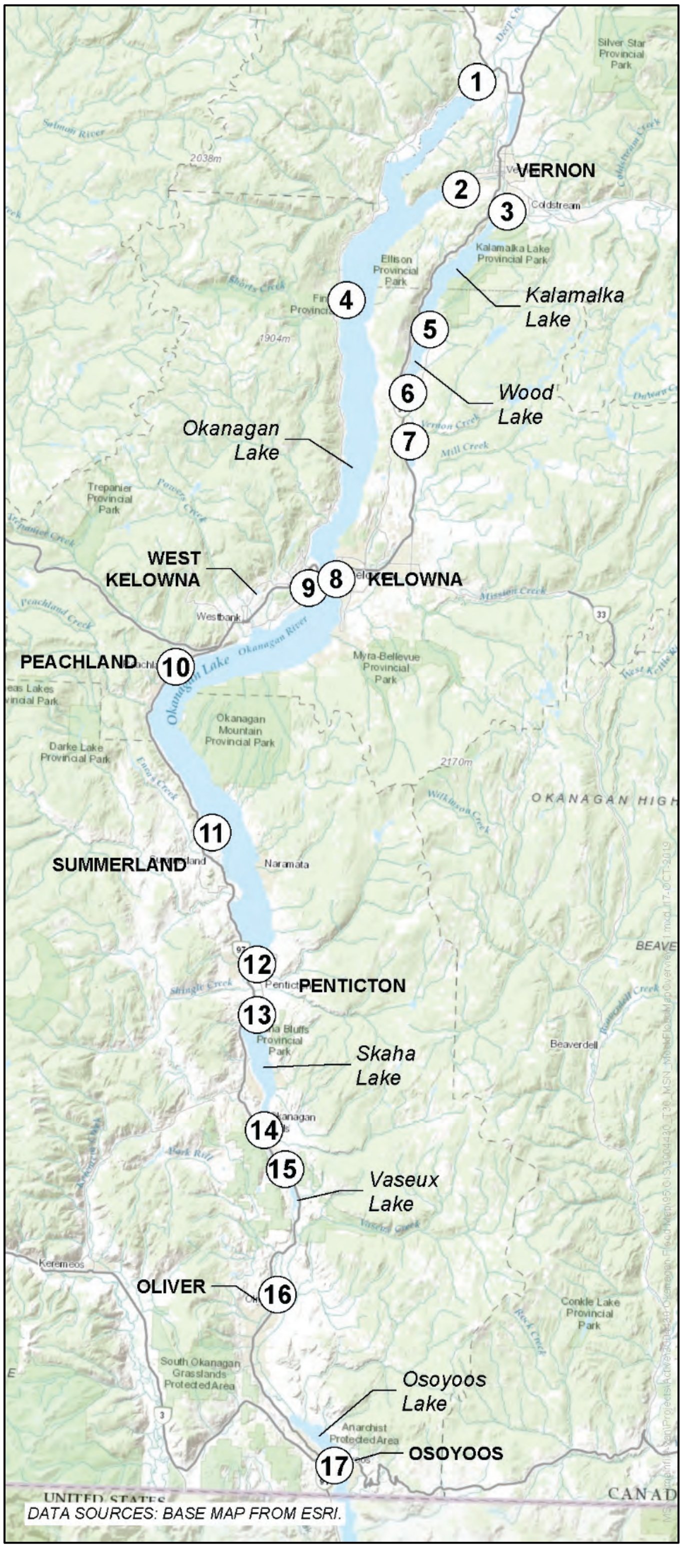


Figure 6-1 Representative points for vertical datum comparison.

Table 6-1 Changes in elevation between vertical datums at representative locations[1].

ID	Location	Latitude	Longitude	Elevation (m, CGVD28 HTv2.0)	Elevation (m, CGVD2013)	Difference in Elevation (m)[2]
1	north end Okanagan Lake	50° 20' 57" N	119° 18' 43" W	343.229	343.561	0.332
2	Vernon Regional Airport	50° 14' 47" N	119° 19' 49" W	345.859	346.157	0.298
3	north end Kalamalka Lake (Coldstream)	50° 13' 35" N	119° 15' 41" W	393.259	393.551	0.292
4	Fintry, west shore Okanagan Lake	50° 8' 16" N	119° 29' 40" W	344.973	345.279	0.306
5	Oyama, south end Kalamalka Lake	50° 6' 43" N	119° 22' 14" W	412.775	413.046	0.271
6	south end Wood Lake	50° 3' 3" N	119° 23' 57" W	394.027	394.295	0.269
7	north end Ellison Lake (Duck Lake Reserve)	50° 0' 18" N	119° 23' 40" W	427.924	428.188	0.264
8	Kelowna, east shore Okanagan Lake	49° 52' 18" N	119° 29' 45" W	343.478	343.722	0.244
9	West Kelowna, west shore Okanagan Lake	49° 51' 45" N	119° 32' 12" W	369.042	369.259	0.217
10	Peachland, west shore Okanagan Lake	49° 46' 58" N	119° 43' 38" W	344.470	344.687	0.217
11	Crescent Beach, west shore Okanagan Lake (Summerland)	49° 37' 35" N	119° 39' 55" W	344.533	344.723	0.190
12	Penticton, south end Okanagan Lake	49° 30' 11" N	119° 35' 37" W	344.275	344.486	0.211
13	Penticton, north end Skaha Lake	49° 27' 17" N	119° 35' 27" W	339.125	339.365	0.240
14	south end Skaha Lake	49° 20' 43" N	119° 34' 29" W	343.872	344.150	0.278
15	north end Vaseux Lake	49° 18' 32" N	119° 32' 31" W	333.043	333.322	0.279
16	Oliver	49° 11' 23" N	119° 32' 48" W	296.284	296.581	0.297
17	Osoyoos	49° 1' 42" N	119° 27' 22" W	280.231	280.468	0.238

[1] Data in this table is provided as an example only. These data points should not be used to transform elevations. Refer to conversion tools such as NRCan's GPS-H tool.
[2] Changes are from CGVD28 HTv2.0_2002 to CGDV2013.

6.2.2 Development

For riverine flood extents, the simulated water level at each cross section from the model was used to generate a water surface. The surface was linearly interpolated along the thalweg between sections and assumed to have a constant level projecting across the floodplain from the thalweg perpendicular to the flow path. The surface was mapped over the DEM. The projected flood inundation extends past dikes and roads to account for potential breach or seepage through or under the embankments (Figure 6-2).

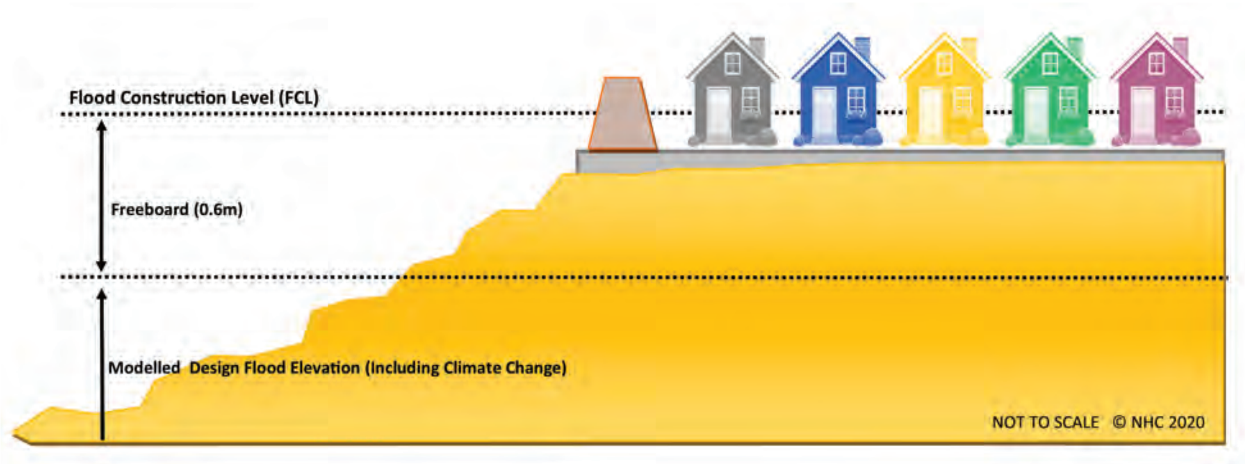


Figure 6-2 Flood construction level schematic for rivers.

FCL is documented on the floodplain maps with labelled Isolines. The FCL for a specific building or space is to be taken as the highest FCL applicable for that location. For riverine FCLs this is the upstream extent of the building or space. Where the building or space is located between isolines, two options exist for determining the applicable FCL:

- Option 1: the FCL is taken as the value represented by the next upstream isoline, or
- Option 2: the FCL is calculated through linear interpolation between the 2 isolines in which upstream face of the building or space is located.

An example is presented below based on the building and mapped isolines shown in Figure 6-3:

- The highlighted FCL line has an elevation of 317.20 m, with the downstream FCL (shown as a black line) having an elevation of 317.00 m. The distance between these lines is 28 m, and the upstream side of the building is 7 m downstream from the 317.20 FCL isoline.
- The FCL for the labelled building using Option 1 is 317.20 m and using Option 2 it is 317.15 m (through interpolation of the FCL using a 0.20 m drop over 28 m).

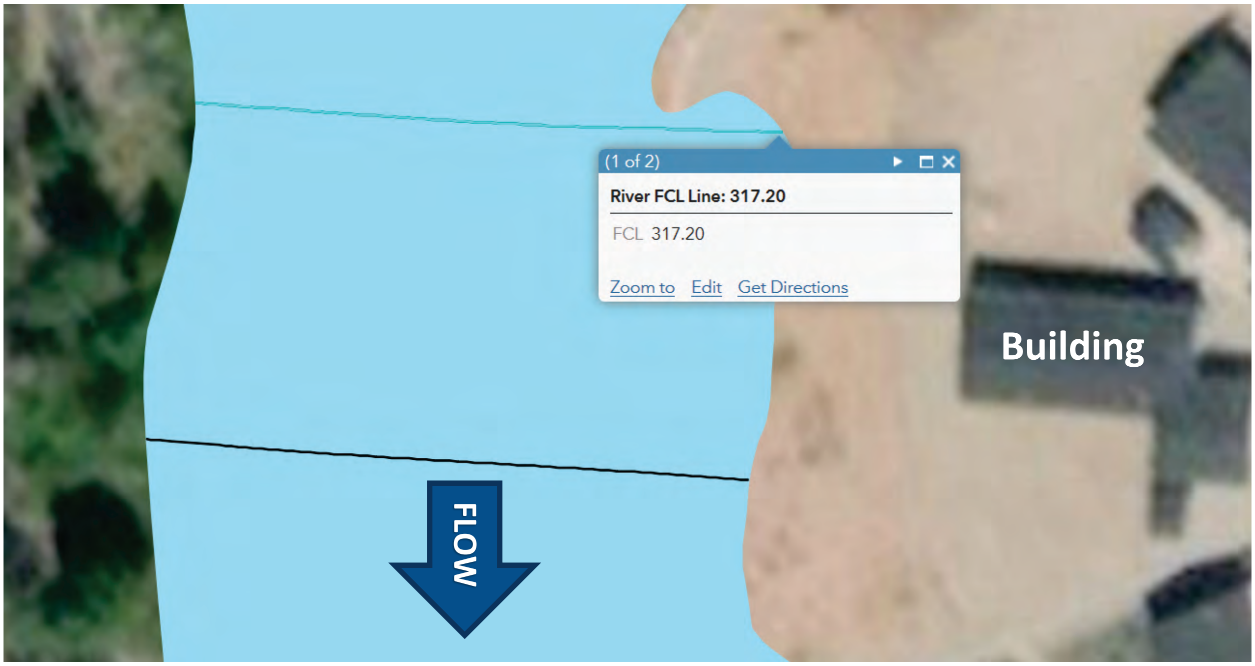


Figure 6-3 Example of river FCL line calculation.

Flooding from the lakes is identified in the mapping through characterization of two hazards – lake inundation and wave effects. Lake inundation is developed through modelling of the flood elevation for each lake, called the 'still-water' level. On top of this still-water level, wind-setup (increase in water level due to the effect of the wind displacing the water in a direction due to shear), and freeboard were added. This elevation (determined for each lake) was projected on the DEM surface to identify the flood extents. The FCLs for the lake inundation zones are comprised of the modelled still-water level, wind setup and freeboard.

Along the shorelines of the lake, additional flooding is expected due to the effects of waves. To show this hazard, a wave effect zone (area which may be impacted by waves) was developed through the following steps:

- The generalized shoreline (where the lake edge typically meets the land) was used as the lakeward edge of the wave effect zone.
- To characterize the waves, a wave model was run to determine wave heights and calculate runup. The model was run twice, for wind events from both the north and the south, and the maximum values were used.
- A wave height line was developed where waves are equal to 0.3 metres in height (a wave height which causes damage based on FEMA guidelines).
- The wave height line was offset 40 metres inland to define the landward edge of the wave effect zone. The line was then smoothed and reviewed to ensure appropriate representation of likely wave effects on the shoreline.

- To determine the height of the FCL, estimated wave runup was added to the lake inundation FCL elevation. See FCL components in Figure 6-4.

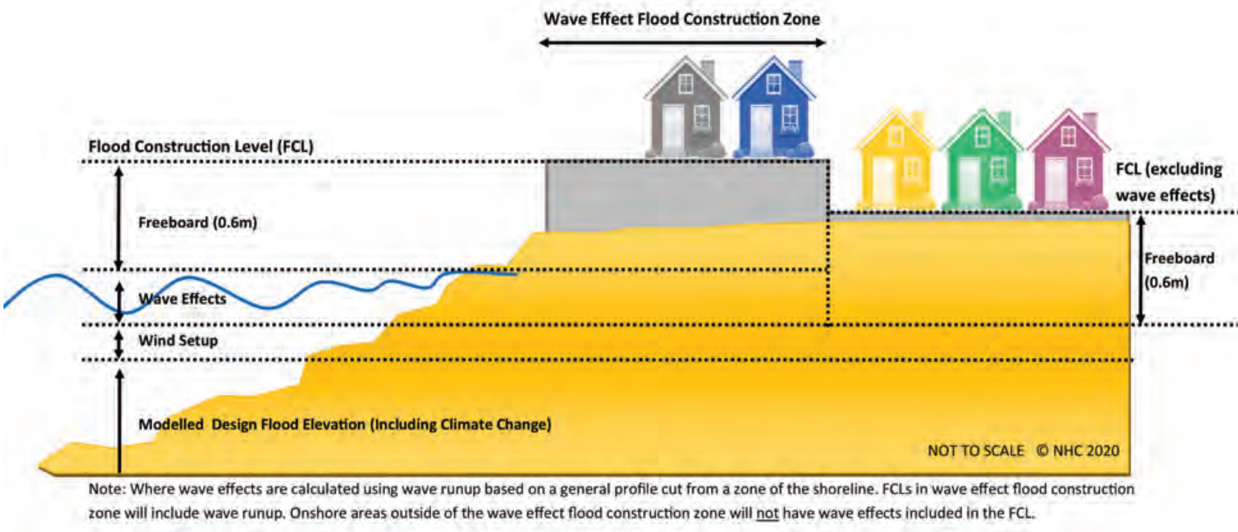


Figure 6-4 Flood construction level schematic for lakes.

Freeboard Requirements

Freeboard is added to provide a safety factor to account for local variations in water level (such as standing waves, super-elevation at the outside of river bends, and local turbulence) and uncertainty in the flood level analysis. Historically in BC, the minimum freeboard allowance applied has been the greater of 0.3 m above the instantaneous (peak) flood event or 0.6 m above the daily flood event. For some rivers, freeboard should be increased to 1 m or more, to address greater uncertainty in the assessment or concerns regarding sediment deposition, debris blockages or ice jams (MWLAP, 2004).

In recent years, a minimum freeboard of 0.6 m has been frequently used with an instantaneous event[1], as suggested in recent provincial guidelines for sea dikes (MOE, 2011) and as discussed in the EGBC professional practice guideline for floodplain mapping (APEGBC, 2017). Considering the uncertainty of climate change on future flood flows, a minimum freeboard allowance of 0.6 m is recommended.

OBWB and local governmental bodies may wish to define a higher level of protection for certain infrastructure or facilities, such as dikes, major transportation routes, hospitals, emergency response centers, communications centers, residences for the elderly, or schools.

[1] A brief set of examples of use of a minimum of 0.6 m freeboard above the instantaneous flood flow within BC include flood hazard study and mapping in Prince George, the lower Fraser River, Maple Ridge, Squamish, Pemberton, and North Vancouver (KWL, 2014, 2017; NHC, 2008b, 2014, 2016, 2018).

6.2.3 Explanation of Layers

Table 6-2 summarizes layers shown on the floodplain maps, as well as additional flood mapping GIS layers described in the following sections.

Table 6-2 Summary of floodplain mapping and GIS layers; climate change is mid-century (2041-2070) except where noted as end of century (2071-2100).

Description	Includes Climate Change	Includes Freeboard	Includes FCL	Extent Polygon	Depth Raster	Velocity Point
LAKE						
FCL shoreline zone	Y	N	Y – on map	Y – on map	N	N
inundation extent – design with freeboard (FCL)	Y	Y	Y – on map	Y – on map	Y	N
inundation extent – design without freeboard	Y	N	N	Y – on map	Y	N
20-year ARI extent	Y	N	N	Y	Y	N
100-year ARI extent	Y	N	N	Y	Y	N
200-year ARI extent	Y	N	N	Y	Y	N
500-year ARI extent	Y (end-of-century)	N	N	Y	Y	N
RIVER - INUNDATION EXTENTS						
river cross sections	Y	Y – where indicated	N.A.	N.A.	N.A.	N.A.
inundation extent – design with freeboard (FCL) and FCL river isoline	Y	Y	Y – on map	Y – on map	Y	N
inundation extent – design without freeboard	Y	N	N	Y – on map	Y	N
20-year ARI extent	Y	N	N	Y	Y	N
100-year ARI extent	Y	N	N	Y	Y	N
500-year ARI event	Y (end-of-century	N	N	Y	Y	N
RIVER – HAZARD						
hazard data - design flood	Y	N	N	N	Y	Y
2017 WATER EXTENTS						
2017 flood edge of water	N.A.	N.A.	N.A.	Y	N.A.	N.A.

6.2.4 Comparison to Previous Flood Mapping

The most recent previous floodplain mapping, 1991, was based on 1D modelling of the Okanagan River from Osoyoos Lake to Okanagan Lake. Direct comparison with the historic maps is challenging due to differences in vertical survey datum. However a spot comparison of FCL between the 1991 maps (roughly converted to CGVD2013) and the current maps suggests an increase in FCL on the order of 0.7 m along Okanagan Lake (Vernon, Kelowna, Peachland, Penticton); this increases to a 1 to 1.2 m increase in FCL through Penticton and Osoyoos Lake, and then reduces to a 0.1 to 0.4 increase in FCL downstream of Okanagan Falls to the USA boarder. Since most of the floodplain is confined by relatively steep slopes, particularly along Okanagan Lake, Skaha Lake, and Osoyoos Lake, the increase in FCL generally only translates to a relatively small increase in extent (typically <100 m but up to 300 m further beyond the source water body).

Several factors have led to the increase in the design flood. These are:

- Design event – for the Okanagan Lake and Wood-Kalamalka Lake, the flood of record (2017 flood) has been selected as the design event. This event has a magnitude similar to the 500-year event. In comparison the past mapping was based on a 200-year event. On Okanagan Lake, the difference between the previous 200-year event and the new 500-year event (both with freeboard) is 0.7 m.
- Design flow – the design inflow has increased for all events (such as the 200-year and the 500-year event). An additional 30 years of flow and climate data has been used to develop the design flow estimates. The current 200-year design flood in Okanagan River output from Okanagan Dam is 56% greater than that used in 1991.
- Design levels – the design levels have increased for both 200-year and 500-year events. This is due to a number of reasons: 1) an additional 30 years of records have been collected; 2) the effect of regulation on the system has been accounted for in the production of design levels and flows through the combined hydrology/reservoir operations models; and 3) the impact of a changing climate (either changes that have already happened or those expected to happen in the future) on inflow timing and volume have been accounted for through ensemble climate simulations, <u>including application of a modified version of the current operational regime of the lake outflow structures</u>. The ensemble climate simulations provided the ability to account for the fact that data collected prior to the 1991 report may no longer be representative of the present-day conditions.
- Freeboard – the current maps have been prepared with a freeboard of 0.6 m. The previous maps which used a variable freeboard that ranged from 0.6 m to 0.8 m. The variable freeboard was to account for wind and wave effects along the lake shoreline in addition to study uncertainties (Ministry of Environment, Lands and Parks Water Management Division, 1992). In contrast, the current study incorporated wind and wave effects directly in the calculated design water level.
- Climate change – the design event for the current maps has been increased to account for climate change to the middle of the current century.

- Shoreline effects – the current lake floodplain maps include an allowance for the calculated wind and wave effects, including wind setup (<0.1 m) and wave runup (as much as 2.7 m), which the previous maps did not include.

In addition to these changes, the 1991 maps are presented in CGVD28 datum instead of CGVD2013 datum. The difference between the datums varies across the study area; with data from the CGVD28 datum increased by 0.2 to 0.3 m to be converted into the CGVD2013 datum. Additional variability in conversion likely exists across the study area dependent on the approach used in preparation of the historic map. The magnitude or extent of this additional variation is unknown and would require extensive discovery and survey of the historic benchmarks to define.

The following tables (Table 6-3 and Table 6-4) provide a comparison of the FCL's presented in the 1991 maps and the current maps.

Table 6-3 Comparison of proposed vs. previous lake level FCLs.

Location of Comparison Point	Previous FCL (CGVD28)	Previous FCL (CGVD2013)	Recommended FCL (excluding wave effects) (CGVD2013)	Approximate increase
Kelowna Hospital	343.66	343.90	344.56	0.66
Peachland	343.66	343.89	344.56	0.67
Okanagan Falls	339.20	339.47	340.63	1.16
Osoyoos	280.70	280.93	281.01	0.08

Table 6-4 Comparison of proposed vs. previous river FCLs.

Location of Comparison Point	Previous FCL (CGVD28)	Previous FCL (CGVD2013)	Recommended FCL (CGVD2013)	Approximate increase
Upstream of Hwy 97 North Bridge in Penticton	341.30	341.52	342.60	1.08
Upstream of Skaha Lake	339.25	339.49	340.70	1.21
Upstream of Vaseux Lake	329.60	329.88	329.90	0.02
Upstream Hwy 97 Bridge in Oliver	307.50	307.79	308.00	0.21
North end of Tuc-El-Nuit Lake	299.00	299.29	299.67	0.38
Upstream of Osoyoos Lake at Road 22 Bridge	280.70	280.95	281.35	0.40

6.3 Additional Flood Mapping Scenarios

In addition to the design flood scenarios shown on the floodplain maps, GIS layers were generated for several other flood scenarios. All flood layers are summarized in Table 6-2.

6.3.1 Development

Riverine and lake flood layers for the 20-year, 100-year, 200-year, and 500-year ARI events were mapped using the approach described above in section 6.3.1. All scenarios include either mid-century or end-of-century climate change effects as noted in Table 6-2. Results were generated without inclusion of freeboard. FCL values and lake wave effect zones were not created for these additional flood scenarios.

As indicated in Table 6-2, layers provided include:

- inundation extent polygons; and
- depth rasters.

6.4 Flood Hazard Layers

River hazard has been mapped using depths and velocities output from the model. This information is most effectively presented by overlaying velocity vectors (arrows indicating direction and magnitude) on top of depth rasters. This will give users an idea of how deep the water is and how fast the water is moving. This is a departure from example approaches presented in guidelines (APEGBC, 2017), which suggest using a composite hazard value derived as a function of depth and velocity. Hazard mapping layers are created without using freeboard.

Since the dikes mostly contain the flood flows for the Okanagan River, and breaching was not included in this study, it was determined that the best approach to approximate flow velocity on the floodplain was to simulate the river as if the dikes were not in place. Three simulations were performed to track floodwaters and understand flood velocities across the floodplain based on Appendix C of FEMA (2013): i) the left dike was removed, ii) the right dike was removed, and iii) both dikes were removed. The largest resulting velocities and depths from these scenarios were used to develop the hazard maps. Due to the simplistic approach used (Appendix C of FEMA, 2013), however, the depth and velocity hazards near the main channel may be underestimated.

Depths are provided as a raster GIS layer with elevations in metres. Depth categories can be presented as recommended in Table 6-5. These categories were adapted from a Japanese national standard (EXCIMAP, 2007), have been applied by NHC for numerous other projects across BC, and are presented in the provincial flood mapping guidelines (APEGBC 2017). Velocity arrows show the magnitude and direction of water movement.

Table 6-5 Depth layer categories.[1]

Depth (m)	Description	Example
< 0.1	most buildings are expected to be dry; underground infrastructure and basements may be flooded	
0.1 – 0.3	water may enter buildings at grade, but most are expected to be dry; walking in moving water or driving is potentially dangerous; underground infrastructure and basement may be flooded	
0.3 – 0.5	Water may enter ground floor of buildings; walking in moving or still water or driving is dangerous; underground infrastructure and basements may be flooded	
0.5 – 1.0	water on ground floor; underground infrastructure and basements flooded; electricity failed; vehicles are commonly carried off roadways	
1.0 – 2.0	ground floor flooded; residents and workers evacuate	
> 2.0	first floor and often higher levels covered by water; residents and workers evacuate	

1. Categories and colours adapted from EXCIMAP (2007) and Flood Control Division, River Bureau, Ministry of Land, Infrastructure and Transport (MLIT) (2005).

An example of the flood hazard outputs is shown for the reach of the Okanagan River south of Vaseux Lake in Figure 6-5. In the second image, the green and yellow areas circled in red on the left bank (east side of the dike) show the calculated depth hazard.

The current study does not include dike break analysis. Typically, such analysis is expected to result in lower flood levels for areas protected by dikes. This example location illustrates how flood levels could potentially be identified as more severe following a dike breach analysis. A breach of the upstream left bank dike at this sample location could result in greater depth and velocity across this area, particularly if floodwaters from the upstream breach were trapped behind the dikes.

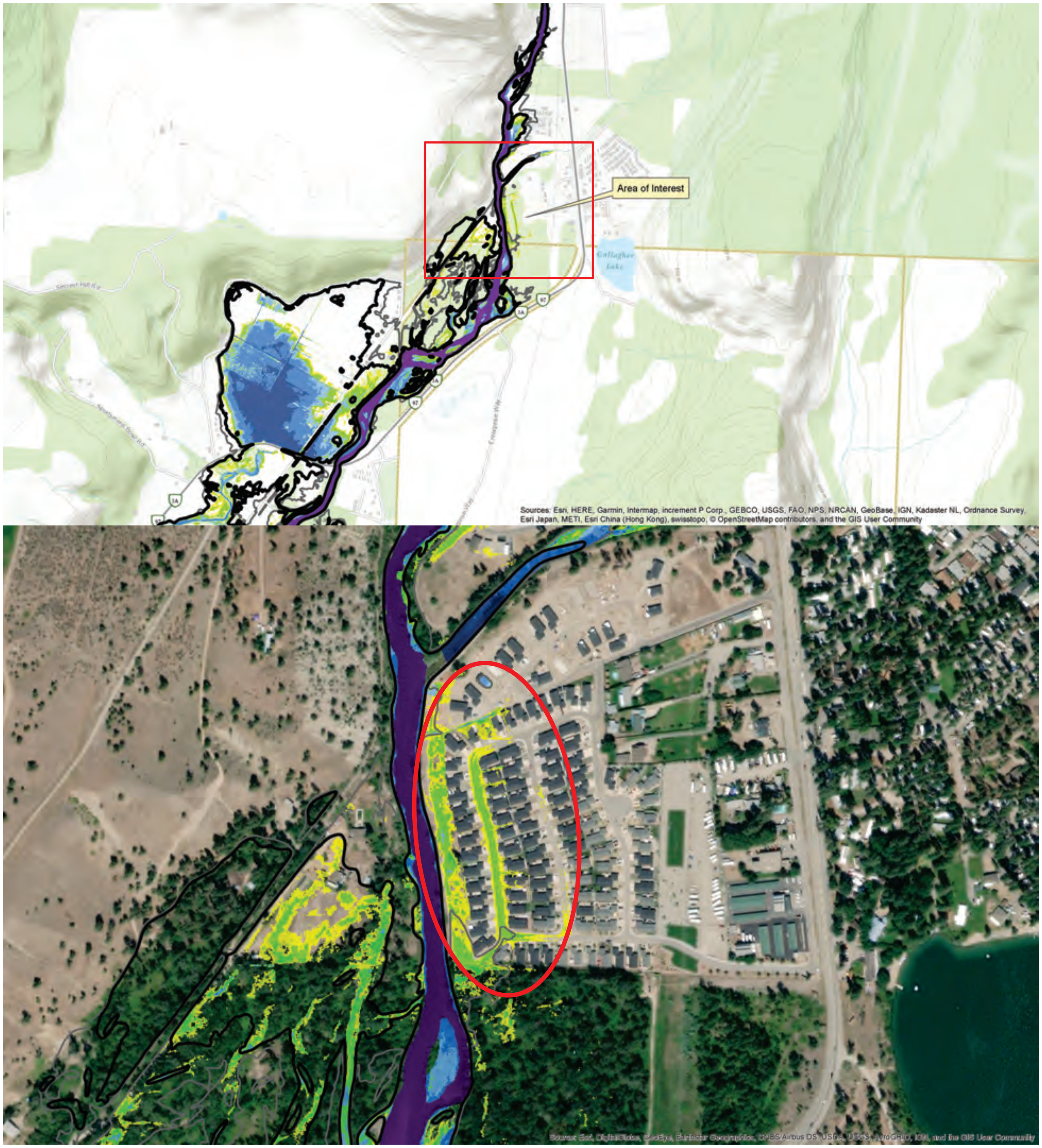


Figure 6-5 Example of flood hazard depth mapping. Top image shows area of interest, bottom image showing detail: coloured hatching (as defined in Table 6-5) illustrate depth hazard category, and black lines delineate flood inundation extent (no freeboard), with grey lines delineating the FCL extent.

6.5 Application to Flood Risk Reduction

The purpose of floodplain mapping is to reduce the risk of floods through improving understanding of the hazard and allowing First Nations, governments, organizations, and individuals to plan for potential floods and reduce their risk.

In 2015, the United Nations developed the Sendai Framework for Disaster Risk Reduction, an international document adopted by 185 United Nations member states including Canada. In 2018, BC adopted the Sendai Framework, and updated the provincial Emergency Program Act (EPA) to align with the framework.

As explained by BC's EPA modernization discussion paper, "The Sendai Framework marks a shift from focusing on emergency preparedness and response to recognizing that risk identification and mitigation are key to managing hazards and reducing the impact of events. It aims for substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries and calls for all of society to share responsibility for reducing disaster risk (Government of British Columbia, 2019)." The Sendai Framework specifies four priorities for action:

- Understanding disaster risk;
- Strengthening disaster risk governance to manage disaster risk;
- Investing in disaster risk reduction for resilience; and
- Enhancing disaster preparedness for effective response and to "build back better" in recovery, rehabilitation, and reconstruction.

The flood mapping of the Okanagan mainstem contributes to the first priority, understanding disaster risk, through improving understanding of the hazard. The flood mapping provides primary information needed to work on the other priorities for action. The application of the floodplain mapping to the other priorities for action within the BC regulatory framework and typical practice is explained in the following sections.

There are two main goals in flood risk reduction best practice (AIDR, 2017):

- Managing flood risk – improving community resilience to flooding and limiting flood risk growth; and
- Maintaining the flood function of the floodplain – ensuring the floodplain can perform its natural functions of flow conveyance and storage through measures such as:
  - maintenance or improvement of the capability of the floodplain to perform its natural function of conveying and storing floodwater (AIDR, 2017)
  - plan for land uses compatible with the flood function of the specific area of the floodplain (AIDR, 2017)
  - maintenance of the capability of the floodplain to support floodplain ecosystems dependent on inundation (AIDR, 2017)

- floodplain and catchment management practices that are ecologically sustainable (AIDR, 2017)

The remainder of this section discusses techniques towards the goal of managing flood risk. Maintaining the flood function of the floodplain should be considered in development of an implementation plan for any measure designed to manage flood risk.

Selection of appropriate flood risk treatments should be based on the risk faced by the area. Risk is based on a combination of likelihood and consequence. The consequences of flooding are determined by studying the hazard (extent of flooding, depth and velocity of water, length of warning, duration of flooding), exposure (what is inundated or affected by the flood), and vulnerability (consequence of exposure). There are several guidelines available for risk assessment in Canada and internationally. In BC, EGBC provides professional practice guidelines for flood risk assessment including:

- Legislated Flood Assessments in a Changing Climate in BC (EGBC, 2018)
- Flood Mapping in BC (APEGBC, 2017)

Nationally, Natural Resources Canada is developing the Federal Flood Mapping Guidelines Series. The Flood Risk Assessment procedures for this guideline series are currently under development by NHC.

In addition to the Sendai Framework, several international examples can be consulted to inform flood risk assessment in Canada including:

- United Kingdom, Framework and Tools for Local Flood Risk Assessment (United Kingdom Department for Environment Food and Rural Affairs, 2014)
- Managing the Floodplain - A Guide to Best Practice in Flood Risk Management in Australia Handbook 7 (AIDR, 2017)

Flood risk information is typically used to inform policy direction and guide flood mitigation planning. Flood risk is dynamic and therefore the approach to floodplain management should also respond to changing climate and development conditions, using an approach such as the Dynamic Adaptive Policy Pathways (DAPP)[1] approach.

A flood risk assessment, which includes considerations of flood hazard, exposure, and vulnerability for multiple categories of receptors is recommended as a next step to support flood risk reduction in the Okanagan valley.

The following subsections illustrate some general examples of mitigation measures that flood risk assessment can be used to identify and inform the prioritization of.

[1] Dynamic Adaptive Policy Pathways (DAPP) is adaptive planning involving continued review and revision of a plan as it is implemented and conditions continue to change, for example as climate change impacts are better understood (https://www.deltares.nl/en/adaptive-pathways/, accessed 31 March 2020).

6.5.1 Structural Mitigation

Structural mitigation aims to reduce the flood hazard. Structural mitigation of floods and control of rivers and lakes has been done extensively in the Okanagan valley through dams, dikes, dredging and channelization. The following sections describe structural mitigation measures and their typical use in BC. With the increases in flooding anticipated due to climate change, existing structural mitigation measures will not provide the same level of protection as they have historically. As such, it is important to consider upgrades to existing structural mitigation measures or use of non-structural mitigation measures as discussed in section 6.5.2.

Flood Barriers

Typical flood barriers include permanent dikes and temporary structures.

Permanent dikes have been used extensively to provide protection from high water as a barrier to hold back ponding or flowing water. Dikes are generally most suited to address flooding of dense communities where the tax base is sufficient to fund both construction and ongoing maintenance. Dikes are often seen as a desirable form of flood protection as they can block water, sediment, and debris from entering a community, protecting it from frequent flood events, however there are many drawbacks:

- High cost expenses include acquiring the land, constructing the dike, monitoring the dike, and maintaining the dike.
- Dikes can limit habitat potential by restricting riparian habitat and acting as a barrier between terrestrial and aquatic habitat, limit space for the river to migrate and store sediment and debris.

- When a dike encroaches on the floodway, it has the potential to increase local velocities, increase water levels, and decrease in-channel storage (which can increase downstream flow).
- Dikes block flow from the flood source (i.e. the Okanagan mainstem), but also prevent outflow from local stormwater, tributaries, and groundwater. Suitable drainage must be provided and maintained for groundwater and channels that flow through dikes. Groundwater can pool behind dikes as it seeps through from the river and beneath dikes and is then unable to drain into the channel.
- Dike breaches through overtopping, surface erosion, internal erosion (piping), or seismic destabilization can be more hazardous and consequential than the flood events that the dikes protect against. Dike failure typically causes significant velocity and depth of flow behind the dike. Dikes can also increase water levels within a diked floodplain if there is an upstream dike breach.

Inset 6-1 Temporary flood barrier in the City of Kelowna, photo courtesy of City of Kelowna - Michael Hintringer

Some of the adverse environmental aspects and costs can be reduced if dikes are setback from the river floodway and erosion protection is set back from the active channel.

Temporary flood barriers are physical systems which are implemented in response to a potentially forecasted flood. They can include temporary dikes, pre-planned sandbag walls and other temporary flood barriers. Temporary flood barriers should be pre-planned through a flood mitigation plan and planning should include consideration of the foundation and procurement of the temporary structure. These systems were used in the 2017 floods in the Okanagan and include sandbags and inflatable flood walls. Correct and timely installation is critical, and these measures are much more suitable for low-velocity locations such as lakeshores than higher velocity locations such as along flowing channels. As with other physical mitigation measures, if placed in the wrong location, they can have an adverse affect on flood behaviour in other areas, impact local drainage and impede emergency access.

Flow Conveyance Improvements

Flow conveyance improvements have been made extensively along the Okanagan River including straightening, widening, dredging and clearing the original, meandering channel. Improving conveyance with these techniques reduces the flood elevation within a given area and immediately upstream. Dredging of accumulated sediment and removal of debris is often done where channel gradients decrease from sediment accumulation. Overtime, sediment can accumulate within channels, effectively constricting flows and causing flood levels to be higher as sedimentation reduces the cross section for water to flow. Dredging and debris removal are an effective strategy to maintain conveyance at culverts and bridges and along channels, however, there are environmental impacts associated with dredging. Dredging causes habitat and vegetation disturbance in streams, often removing the vital components of aquatic habitat.

Diverting water around a community through diversion channels is also possible. Large scale diversion of flow is typically only suitable when protecting a large community and where there is room to route flood flows (such as the Red River floodway around Winnipeg). In the Okanagan valley, the large lakes and surrounding development occupy much of the space where diversion could be considered.

Flow conveyance improvements can be implemented with a focus on naturalization. Dikes can be set back, and relic channels can be restored to increase conveyance. Reconnecting and rewatering oxbows which were removed from the river channel through straightening can improve flow conveyance and have significant habitat value.

Flood Flow Reduction

Upstream storage can be used to attenuate flood flows. There are numerous dams on the Okanagan River with sizable reservoirs (lakes) which are operated for the purpose of flood reduction as well as many other priorities. Dam operation can mitigate downstream flooding by prolonging and subsequently reducing the peak flow downstream. In order to also reduce upstream flooding (i.e. lake shoreline flooding) the operator may need to lower lake levels in anticipation of high inflows. Operation of the Okanagan mainstem dams will continue to change as the understanding of climate change evolves and other agreements related to the operation of the dam are updated. Due to the uncertainty in the timing and magnitude of future flows expected with climate change, dam operators will be increasingly challenged in determining when to lower upstream lake levels. The uncertainty is expected to result in the dams being less effective for flood mitigation in the future. The addition of dams on substantial tributaries could provide further flood mitigation; however, the scale of available storage is expected to limit their effectiveness. Furthermore, there are large financial, environmental, and societal costs as well as increased risks (such as potential for dam failure) associated with development of new dams, suggesting that such opportunities unlikely to be feasible.

Upstream wetland restoration and recreating marshy areas increases flood storage and habitat values while naturally attenuating flood events. These techniques simultaneously increase flood storage while providing habitat value. However, the scale of flooding along the Okanagan River is not expected to be substantially impacted by such approaches.

Erosion Protection

Erosion protection is typically the armouring of banks with angular rock riprap. Erosion protection on its own does not provide protection from high water levels but can limit erosion and channel migration which can threaten dikes, homes, and other infrastructure located near fast flowing water. See Inset 6-2 for a photo of erosion threatening the stability of a road.

Erosion protection has similar challenges to dikes, predominantly the cost of land acquisition, construction, monitoring, and maintenance, impact to riparian vegetation, installation of a barrier between terrestrial and aquatic habitat, and potentially constricting the natural width and migration of the river resulting in local scour or increased probability of lateral migration on the opposite bank. Some of the adverse environmental aspects of erosion protection can be reduced if the armouring is set back from the active channel or by incorporating planting of shrubs in benches, pockets, or riprap voids.

Inset 6-2 Erosion resulting from the 2018 freshet, photo courtesy of the RDOS.

Riprap spurs (also referred to as groynes) and bendway weirs can be used in conjunction or as an alternative to linear bank armouring. These structures extend rock roughly perpendicular to the bank instead of parallel to the bank. When working properly, these structures reduce the velocity along the bank and can direct flow towards the centre or opposite bank. Often these structures require similar or more rock than linear bank armouring, however effective redirection of flow can limit the length of bank armouring required and potentially reduced maintenance along the bank. Furthermore, such structures create variable hydraulic conditions and can incorporate large wood debris and planting; all of which is often seen as beneficial to aquatic habitat and can therefore support permit acquisition.

To remain functional, erosion control measures require annual inspections and maintenance (especially when large woody debris are incorporated).

Monitoring and Maintenance

Many of the tributary flood conditions may be exasperated by blockage of crossings. Monitoring and subsequent removal of debris and sediment from these culverts and their entrances should be done routinely throughout the high flow season to ensure flow is not further restricted at these locations. In addition, any dikes or other flood protection infrastructure should be inspected annually and maintained as needed. Operation, maintenance, and surveillance documents should exist for key flood mitigation infrastructure to help guide this process.

6.5.2 Non-structural Mitigation

Non-structural mitigation seeks to reduce risk through reducing exposure and consequence. Non-structural mitigations include land-use management, flood proofing and community education. Non-structural mitigation is typically applied even if structural mitigation is used.

Land-Use Management

The province provides guidelines to help local governments develop and implement land-use management plans and make development decisions for flood hazard areas (FLNRORD, 2018). Development decisions may include limiting land use and density within certain hazard zones and or requiring site specific hazard assessment and mitigation measures for development within hazard zones (i.e. EGBC, 2018). Part 14 of the *Local Government Act* (Land Title Act 1996) provides local governments with several land-use management tools to promote flood safety. For example, the Act empowers local authorities to establish development permit areas, designate certain lands as floodplains through bylaws, enact zones to promote safe developments in floodplains, and implement measures such as setback from the rivers edge and preventing disturbance of riparian vegetation.

Any development within the floodplain should only be done following a site-specific flood hazard assessment conducted by a registered professional following the EGBC guidelines for such assessments (2018). Assessments may be waived by regulators if the flood risk and any mitigation measures are well known; for example, development within an existing community, behind a regulated dike, with current floodplain mapping. Specific land-use management measures include zoning, development permit areas, setbacks and relocation or managed retreat. There is some overlap in implementation of these techniques, and they can be implemented in conjunction with each other.

Zoning – Some communities have allowed limited development within the floodplain for specific land use (i.e. agriculture and recreation) or on pre-existing lots that otherwise would not be buildable. Such allowances should be reviewed and only approved if deemed safe for use and do not transfer flood risk to other properties. Covenants and occasionally other communications (such as signage, or warnings in lease agreements) are typically a condition of such developments to ensure future landowners and users are aware of the risk. Evacuation planning for humans, animals, and potentially goods of value and potentially damaged by floodwaters should be considered prior to development.

Development Permit Areas – Development permits areas are another land use management tool to ensure that specific requirements are met within hazard areas. They can specify conditions such as flood construction levels and requirement for a property-specific hazard assessment. These can be used in conjunction with zoning.

Setbacks from Waterways – Typically, mitigation measures include set back from the top of bank, water’s edge or dike by a defined amount. Setback as a mitigation measure should also consider remnant side channels that may reactivate during high flow events and groundwater conditions in the area.

Relocation or Managed Retreat – When a community decides to retreat from an area, development planning can operate over long time-horizons. Existing homes and infrastructure can relocate or gradually retreat with time. In areas deemed to high risk or too difficult to protect from flooding, relocation and retreat should be considered. This can include relocation over time through natural property turnover or government appropriation of properties.

Relocation of individual homes may be warranted when homes are located within an area at risk to erosion and channel migration. On going maintenance and repair of bank armouring can be costly and difficult to reduce the risk to an acceptable level, particularly if the channel is actively migrating towards a house (in comparison to local erosion), if there is little bank remaining between the home and the river, or where the site is along a deep scour hole, relocation of one or more homes may be the least costly and most long-term approach to address the flood hazard.

Flood Proofing Individual Assets

This often includes constructing or raising buildings to the FCL but can also include waterproofing of the portion of structures located below the FCL. Local government adoption of a floodplain bylaw under Section 524 of the *Local Government Act* and construction of the habitable areas of new homes to the FCL is a common mitigation approach in BC. Elevation of habitable areas is an effective mitigation measure regardless of the presence of dikes to account for the potential for dikes to fail as well as any groundwater seepage or stormwater inflows that may raise water levels on the landside of the dike.

Community resilience can be increased in the following general ways:

- Raising valuables above the FCL;
- Developing plans for the continuation of business operations in the case of flooding;
- Anchoring potential floating assets (e.g. propane tanks);
- Storing or protecting contaminants up to the FCL; and
- Planning exits, posting warning signs, developing closure plans, etc.

Flood Prediction and Warning

Accurate and timely flood prediction and warning has a significant impact on short-term community preparedness. Adequate flood prediction and warning enables relocation of sensitive assets and vulnerable people, effective evacuation if required, and implementation of any temporary flood barriers. Flood prediction requires robust scientific understanding; accurate, detailed measurements of snowfall and precipitation; robust weather forecasting; and clear dam operation rules. Flood warning must be clear, consistent and informative.

Flood Emergency Response Planning

Emergency response planning (ERP) is critical to identify what actions, when, and by whom need to occur during an emergency to ensure public safety. The ERP may be on a community or district scale. The floodplain mapping can help guide the ERP in identifying areas at risk to flooding and high ground safe areas. Of particular interest should be access routes (highways, railways, airports), emergency centres (RCMP, EOCs, fire stations, hospitals), and large social spaces such as schools and libraries. The hazard mapping may be used in advance of a flood or during a flood to identify likely high velocity and depth areas to avoid.

Preparation of emergency response plans (ERP) by local authorities is mandated by the BC *Emergency Program Act* (Anon, 1996). The province provides guidance on planning for various aspects of flood emergency response including plan preparation, pre- and during-flood actions, and post-flood management. (BC, 2016; PEP, 1999).

Community Recovery Plans

Having a recovery plan in advance of a flood event can significantly improve the efficiency of flood recoveries through having designated roles, clear sources of funding, pre-organized volunteer networks, and plans to meet other anticipated community needs. A thorough community recovery plan decreases confusion and anxiety, facilitates effective coordination between individuals responsible and helps communities come together to help each other effectively after a flood.

Community Awareness

A provincial review of floods and wildfires (BCFWR, 2018) identified dissemination of awareness and education as one of the key pillars of a complete flood mitigation plan. Flood mapping is identified as the first step of awareness of the hazard (NRC/PSC, 2018). Despite preparation of the floodplain map, distribution and education should shortly follow. A provincial review of floods and wildfires (BCFWR, 2018) identified dissemination of awareness and education as one of the key pillars of a complete flood mitigation plan. Flood mapping is identified as the first step of awareness of the hazard (NRC/PSC, 2018). Despite preparation of the floodplain map, distribution and education should shortly follow.

The Project ArcGIS Hub is intended to serve as a key source of information about the potential flood hazard in the Okanagan. This page includes information digestible by a wide audience about the flood hazard and resources for preparation and risk reduction (see section 6.5.3).

Inset 6-3 Sandbagging competition in Skagit County.

With a datum shift and an expanded flood plain defined due to changes in modelling and climate change, community conversations are needed as people that may have once considered themselves safe from a flood may now be within the floodplain and should be made aware of the risk.

Education about flood risk can help inform property owners to help them be more prepared. Flood risk education can include:

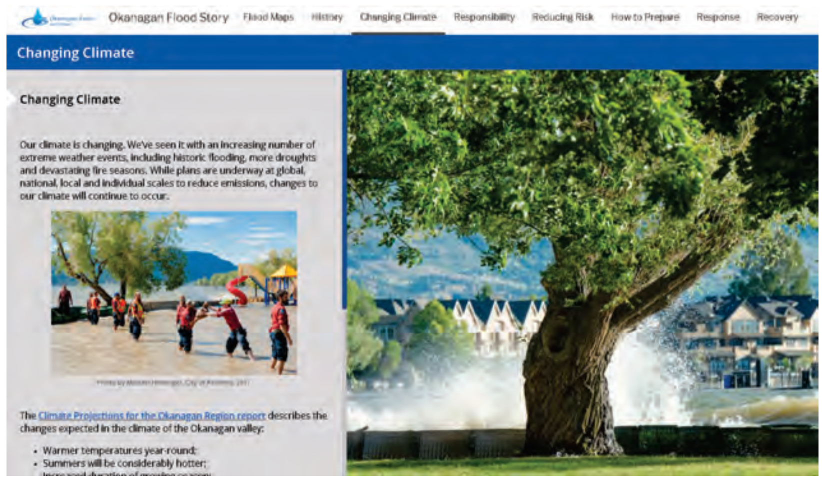
- Presenting the new flood mapping and updated understanding of current and future flood hazard (i.e. floodplain FCL, depth, velocity, or hazard maps);
- How to prepare for and be aware of the timing and seasonality of floods;
- Where to find sources for information on floods and flood preparedness;
- Community resources with respect to flooding (such as information from Okanagan Basin Water Board, BC Flood Forecast Centre, local government websites);

- Where to find real time forecasts of water level, water flow, and what it means; and
- Local evacuation routes, notifications, procedures and high ground.

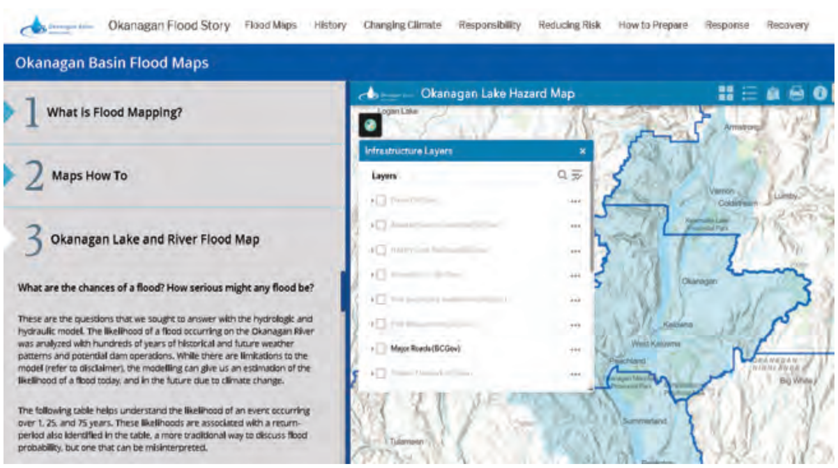
Community outreach can take the form of websites, handouts, news articles, community meetings, and poster and booth presentations at community events (i.e. county fair). Some diking districts hold spring sandbag competitions to build awareness of the upcoming flood season (i.e. Inset 6-3, courtesy Skagit County).

6.5.3 Project Website

To share the potential flood hazard information with the public, an interactive and informative online website was developed. The website is hosted on ArcGIS Hub, and contains a narrative of the flooding within the Okanagan valley. The purpose of the website is to inform the public about the potential flood hazard in context with the local environment and provide the public with comprehensive resources to reduce their flood risk. The information is intended to be non-technical and provide resources with more information. Images of the website are provided in Inset 6-4 and Inset 6-5. The website includes the following pages:



Inset 6-4 Okanagan Flood Story website changing climate webpage.



Inset 6-5 Okanagan Flood Story website flood map webpage.

- Landing page – an introduction to flooding in the Okanagan and an overview of the website as well as a disclaimer about the use of the flood mapping which must be accepted
- Flood Maps – a custom explanatory video introduces flood mapping concepts, the mainstem flood maps are presented, related creek flood hazard information is provided, and freshet aerial photos are provided from the 2017 flood

- History – dates and photos of major floods and mitigation efforts in the Okanagan valley are presented in a geographical timeline
- Changing Climate – expected changes to the local climate and the impacts of these changes on flooding are identified
- Responsibility – division of flood responsibility between property owners, local governments, and First Nations, provincial and federal governments are identified
- Reducing Risk – strategies for reducing flood risk for homeowners and communities are identified
- How to Prepare – resources about preparing for a flood are provided through links to government websites
- Response – resources about flood response, flood warnings and advisory notifications and emergency alerts and orders are provided through links to government websites and maps
- Recovery – resources about recovering from a flood are provided through links to government websites

The website was developed with assistance, information and input from a variety of local governments and is intended as a resource for residents from many local jurisdictions. The development of the website and flood mapping included a half day workshop with First Nation and local government representatives. In the workshop, information was collected about local priorities for information, suggested flood mapping look and feel, and interest in ARIs.

6.6 Conclusions, Recommendations, and Future Work

Recommendations for future work include:

- Share the flood hazard with local communities through in-person workshops and discussions to ensure the information is available and accessible. These workshops help inform the community about the understanding of the hazard developed to date, identify what matters to the community and stakeholders, and educate people on the issues and options, as well as identify and build momentum for next steps.
- Evaluate and optimize the operating regime for flow control structures along the Okanagan River to maximize the effectiveness of flood control with consideration of the other environmental, cultural, agricultural, and recreational requirements on the lakes and rivers.
- Develop of a comprehensive risk reduction plan. This plan should take a risk-based approach to flood mitigation, include stakeholder priorities, be developed for the short, medium and long term, include consideration of climate change, and strive for consistency between jurisdictions. The key steps in this plan are:
  - Assess existing structural and non-structural flood mitigation measures;
  - Conduct a flood risk assessment to identify areas of high risk and in greatest need of further flood mitigation, and help prioritize mitigation measures; and,

- Identify structural and non-structural risk mitigation measures and develop an actionable plan to implement the measures.

- Re-evaluate and maintain studies associated with the plan including floodplain mapping, risk assessment, and mitigation planning to reflect changes in risk related to hazard likelihood or consequence. Flood hazard maps should be reviewed at least every 10 years and updated if there are changes to conditions such as the design event, channel geometry, new flood hazards, dike construction, or floodplain development, as recommended by EGBC (APEGBC, 2017).

CHAPTER 7 PRIMARY RECOMMENDATIONS

Chapter 3 through to Chapter 6 provide detailed recommendations at the end of each chapter for those study components. The reader is referred to each of those chapters for a complete list of recommendations as these are not re-summarized here. This chapter provides the primary recommendations from this study with additional detail provided to assist in any future work. The first recommendation listed, update of the operational guidelines, is a preeminent recommendation as it is required to help ensure the flood hazard for the design event is not greater than that presented in the report and accompanying maps.

7.1 Critical Study Assumption: Modifications to the OLRS Operating Plan

The floodplain maps produced from this study are based on inflows projected to the middle of this century. Magnitudes of the design events are expected to exceed the capacity of the existing infrastructure if operational rules are not adjusted to account for the changing climate. Preliminary modifications to the OLRS Operating plan and guidelines were developed to mitigate projected future increases in floods. If these modifications, or similar mitigations, are not implemented, then the resulting flood flows and levels of the design events are expected to be more severe than mapped.

The preliminary modifications were based solely on flood control. Prior to implementation, any changes to the operational plan is expected to require review initially with the Okanagan Nation Alliance and Canadian Okanagan Basin Technical Working Group (COBTWG) and then with a wider stakeholder group. Given the currently projected rate of change in floods due to climate change, review and subsequent implementation of revised operational rules is recommended within the next five years. The Raven ORB model can be used to explore and optimize different OLRS operation schemes for current and projected conditions. At the time of this future review, any updates to climate projections should be reviewed to assess the most up-to-date expectations on future climate.

The climate projections used for this study followed the most recent, accepted projections available; that is, World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 5 (CMIP5)[1], which was undertaken by the WCRP in support of the IPCC 5th Assessment Report[2]. Climate models have recently been updated with Coupled Model Intercomparison Project Phase 6 (CMIP6) [3]. Release of these results is scheduled for 2020; the IPCC 6th Assessment Report is due for release in 2022[4].

7.2 Okanagan Lake Dam and Mainstem Dams

This study did not include an assessment of the consequence of dams overtopping, malfunctioning, dam failure, or the mainstem dams not being operated as designed.

[1] https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip5 , accessed 31 March 2020.

[2] https://www.ipcc.ch/report/ar5/syr/ , accessed 31 March 2020.

[3] https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6 , accessed 31 March 2020.

[4] https://www.ipcc.ch/report/sixth-assessment-report-cycle/ , accessed 31 March 2020.

The 2017 freshet resulted in peak lake levels in Kalamalka and Okanagan lakes that exceeded their previously estimated 200-year ARI level (1991 floodplain mapping), and were the highest levels that have occurred since the dams were built (AE, 2017b). Temporary flood barriers (sandbags) on the west side of Okanagan Lake Dam were necessary during the 2017 freshet peak to contain water within the lake and prevent flow around the west side of the main dam and over the (lower) adjacent land (see Photo 1-2). Based on the Lidar data used in this study, the elevation of the adjacent land (~343.12 m CGVD2013) to the west of the dam is lower than the dam crest, and the water level at the time of the 2017 Lidar (343.479 m CGVD2013), which was 0.36 m higher than ground. Preliminary simulation of the maximum flow that could reach the Okanagan River downstream of the dam if the temporary barriers failed, is approximately 275 m^3/s. This is more than double the design flood from Okanagan Dam used for the floodplain mapping of this reach (Table 3-32).

The scope of the current study did not include dam or dike breach analysis. Typically dam breach analysis is conducted as part of a dam safety analysis by the dam owner and is not incorporated in floodplain mapping or mitigation analysis. While the simulation of flow around the dam is preliminary and should not be used for any assessment, it highlights a risk that is recommended to be evaluated by the dam owner. The following is a list of dam-related study recommendations:

- Low elevation land to the west and east of Okanagan Lake Dam should be evaluated along with the risk of overflow during flood events. Mitigation measures should be identified and planned for as appropriate.
- Develop formal high-water operating rules and/or emergency plans for each reservoir.
- Risk of dam operations (e.g. blockage or malfunction) that could lead to rapid and/or uncontrolled rise in lake levels, or rapid drawdown and release to the downstream channel should be assessed.
- Infrastructure upgrades should be investigated for each dam with two objectives:
    - Increasing outflow capacity from Okanagan and Kalamalka lakes so that rapidly rising water levels can be responded to more quickly than is currently possible; and,
    - Increasing the capacity of the Okanagan River (e.g. reactivation of side channels, lower floodplain levels, set back dikes) for fish habitat and to increase flow conveyance and also dissipate flood flows. Opportunities that improve fish habitat should be prioritized.
- The current Raven ORB model coupled with hydraulic models of the dams could be used for future Dam Safety reviews, including simulation of the PMF with some model refinement. This can aid in assessing dam breach scenarios, reviewing the mainstem dam consequence classifications (CDA, 2013), and improving emergency response plans.
- As larger flood events become more common and the climate and hydrology of the basin change, it is likely that infrastructure upgrades will become necessary. It should be expected by dam owners that their infrastructure will have to be reassessed and potentially upgraded, possibly multiple times over the coming decades, as climate of the Okanagan region continues to change.

- Further refinement of the rating curves for each dam is recommended to improve reliability in the understanding of discharge through the structures during emergency spills. Limited rating curves, consisting of a one gate open scenario, currently exist for the flow control gates at the outlet of Kalamalka-Wood, Okanagan, Skaha, and Vaseux lakes (WaterSmith Research Inc & Streamworks Consulting Inc, 2014). While total outflow is currently monitored with the use of near real-time discharge data from downstream gauges, this does not allow for such well-informed operations in the case of an outage (during which the real-time data may not be available), which could potentially be needed during an emergency. The real-time gauge data is also reliant on rating curves specifically developed for the river, which may shift and are preliminary until reviewed and published by WSC, with the discharge data reported by the gauge being uncertain during operation.

7.3 Climate Data and Flood Forecasting

The following recommendations are provided for climate monitoring and flow forecasting:

- Automating high-elevation climate stations for which the data is currently manually collected or on a volunteer observer network:
  - It was identified that the ECCC Vernon Silverstar (1128584) is missing most of the critical temperature and precipitation data from the pre-freshet/freshet periods (April-June) for 2016-2019 due to the manual data collection being intermittent. This station's data is being used in the development of climate grids by NRCan[1] and PCIC[2], and being the only higher elevation EC station in the Okanagan Valley, it influences the interpretation of high elevation precipitation and temperature in the development of the climate grids. As a result of the missing station data, the climate grids for 2016 and 2017 were erroneous (as identified through comparison to SWE data from high elevation snow pillows, which are not directly used in climate grid generation) and could not be used to simulate these freshets with the hydrologic model.
- Include SWE data directly in the generation of future climate grids.
- Installing additional high-elevation climate stations with the number and distribution throughout the ORB based on an assessment of the spatial variability of climate and apparent gaps.
- Improve lower elevation snow monitoring and include this data in flow forecasting models.
- The Raven ORB model could be used for improved water supply forecasting in the basin; however, it is expected that over time, current forecasting methods will be inadequate due to changing peak timing and the approach to forecasting will need to be re-examined in the

[1] https://cfs.nrcan.gc.ca/projects/3, accessed 31 March 2020.

[2] https://www.pacificclimate.org/, accessed 31 March 2020.

future. This could involve further exploration into improving long-term forecasting of inflows to the ORB.

- It is recommended that the influence of the Similkameen-Okanogan confluence on Osoyoos Lake levels be simulated with a hydraulic model, and that these results be used to develop a three-dimensional relationship between Similkameen River flow, Okanogan River at Oroville flow, and Osoyoos Lake water level. This relationship could then be used to link a Similkameen hydrologic model to the Raven ORB hydrologic model.

7.4 Mainstem Lakes Data Collection and Further Study

The wave results in this study are limited by the accuracy of the data used. Assessing the impacts of wind and waves on the mainstem lake shorelines could be improved in the following ways:

- Bathymetric surveys (particularly in the nearshore) could improve the accuracy of the nearshore wave results; the available bathymetry for several lakes is particularly coarse, including the narrowing of Osoyoos Lake at Highway 3. This data would improve site specific assessments (but could be collected as such assessment are conducted) in addition it would improve any future revisions to the current study. Site specific assessment is recommended for any locations that appear to vary from the referenced generalized shoreline profile or for sizable developments.
- Implementation of wind and wave buoy data collection on Okanagan Lake. Wave data was not available for this study and was simulated without model calibration; wind data was used from Penticton and Kelowna along with short term wind data collected on the lake in a past study (Spence and Hedstrom, 2015).
- Landslide generated tsunamis have been documented in Okanagan Lake over the last 80 years and can result in runup in excess of that calculated for the wind generated wave events. More detailed study of potential landslide zones, the generation and propagation of tsunamis, and subsequent runup zones should be conducted and added to the floodplain maps. Further work is recommended in assessing tsunami hazard in the Okanagan Valley overall, and that this be provided at minimum as information on floodplain maps or included in FCLs where relevant.

7.5 River and Dikes

The Okanagan River dikes generally contain large floods, but these could fail through stability and seepage mechanisms and can breach even if not overtopped. Where vulnerabilities exist is where the dikes are overtopped and where non-gated culverts are present. The open culverts are a source of floodwater onto the floodplain and can contribute a significant amount of water that can spread a large distance during a long flood. During high flows, particular attention should be paid to the dikes to ensure they are not overtopping, eroding, and that piping through / under the dike is not occurring. If the dike should fail, a large amount of water could access the floodplain. It should be noted that while non-gated culverts may increase flood risk on the landside of the dikes, they may also act to reduce dike geotechnical failure risk by reducing the differential head across a dike.

Dike assessments and surveys were not completed as part of this study but are recommended for future work. A dike vulnerability assessment would help identify low and weak spots in the dikes and show the available freeboard. Dike crest surveys could be used to update the dike crest heights used in the modelling to support future dike investigations for the Okanagan Basin.

7.6 Flood Event Monitoring

HWMs should be collected during all flood flow events (i.e. floods in excess of the 10-year flood). This information is useful for model calibration and validation, which should be done following any large flood event. The HWM's should be taken along the entire profile of the modelled reach with sufficient spacing to capture any substantial breaks in slope (i.e. such as upstream and downstream of all hydraulic structures and any constrictions or change in slope). The HWM's for a particular flood event should be collected at the same flow, ideally near the peak of the flood event. The HWM can be staked during the flood and surveyed after it recedes as long as the duration is not so long following the flood that the HWMs maybe damaged or moved.

7.7 Floodplain Mapping, Applications, and Website

Recommendations for future work include:

- Keep the study and website live and up-to-date and continue to share the information on flood hazard with local communities through in-person workshops and discussions to ensure the information is available and accessible. These workshops help the community through dissemination of information about the hazard, identifying what matters to the community and stakeholders, educating people on the issues and options, as well as identifying and building momentum to proceed with further flood risk reduction measures.
- Develop a comprehensive risk reduction plan. This plan should take a risk-based approach to flood mitigation, include stakeholder priorities, be developed for the short, medium, and long term, consider climate change, and strive for consistency between jurisdictions. Key steps in plan development are:
  - Assessment of existing structural and non-structural flood mitigation measures;
  - Assessment of flood risk to identify areas of high risk and in greatest need of further flood mitigation, and to inform prioritization of mitigation measures; and,
  - Identification of structural and non-structural risk mitigation measures and development of an actionable plan to implement the measures.

Re-evaluate and maintain studies associated with the plan including floodplain mapping, risk assessment, and mitigation planning to reflect changes in risk related to hazard likelihood or consequence. Flood hazard maps should be reviewed at least every 10 years and updated if there are changes to conditions such as the design flood, channel geometry, new flood hazards, dike construction, or floodplain development, as recommended by EGBC (APEGBC, 2017).

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