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.

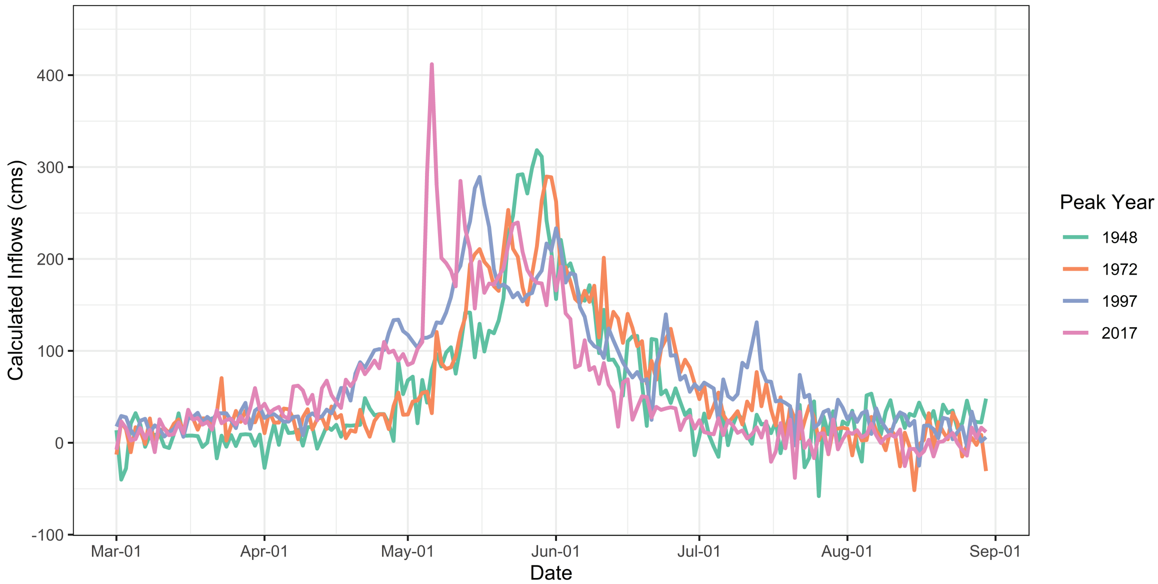


Figure 3-1 Calculated inflows to Okanagan Lake for select peak years.

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.

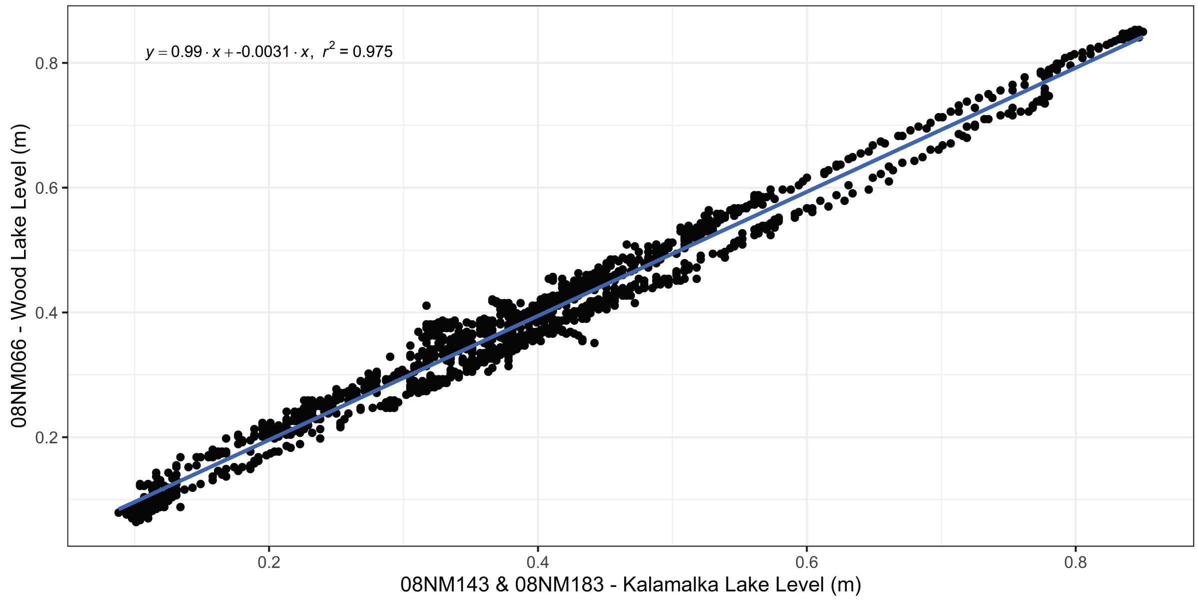


Figure 3-2 Comparison of Kalamalka and Wood Lake Levels.

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 (km²)[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.

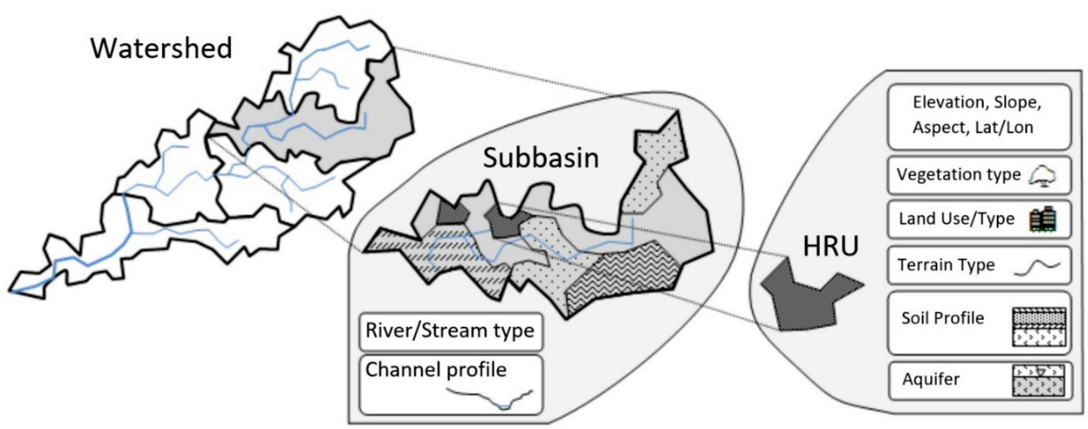


Figure 3-3 Basin discretization in the generalized Raven spatial configuration (Craig and the Raven Development Team, 2019).

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

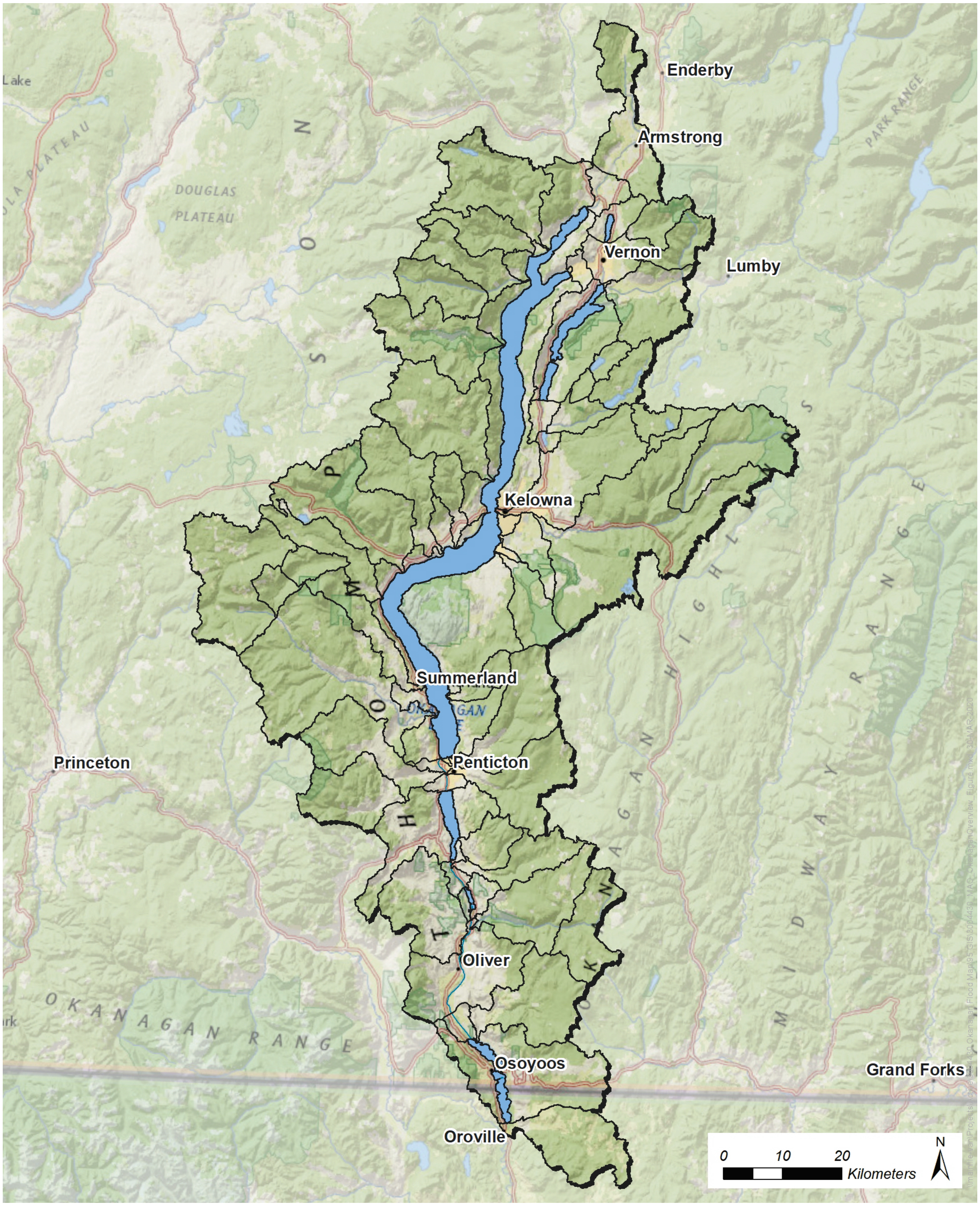
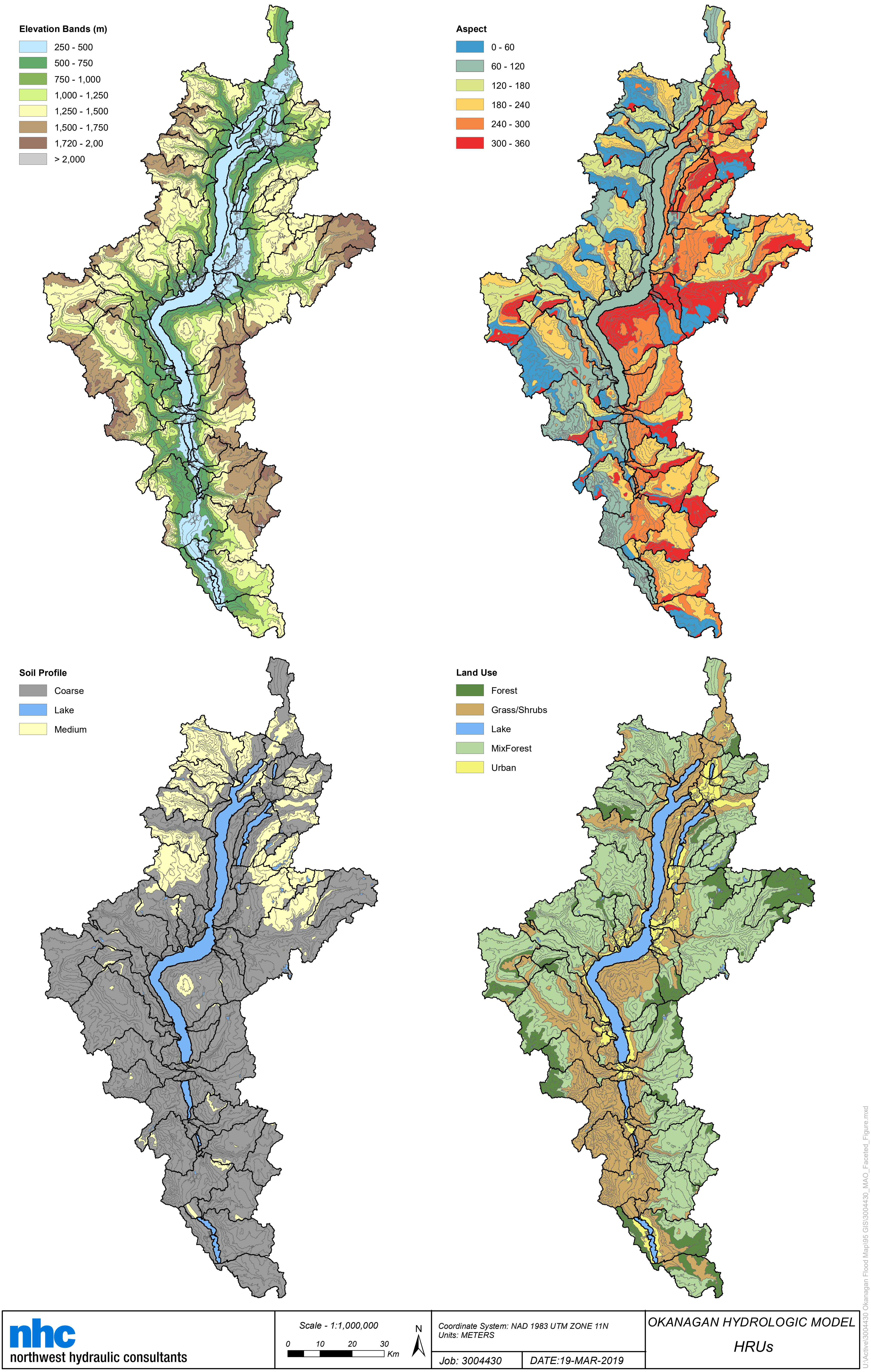


Figure 3-4 Major subbasins of the ORB. Basemap via ESRI.



Elevation Bands (m)
250 - 500
500 - 750
750 - 1,000
1,000 - 1,250
1,250 - 1,500
1,500 - 1,750
1,720 - 2,00
> 2,000
Aspect
0 - 60
60 - 120
120 - 180
180 - 240
240 - 300
300 - 360
Soil Profile
Coarse
Lake
Medium
Land Use
Forest
Grass/Shrubs
Lake
MixForest
Urban
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°C, open water evaporation was also set to 0; a simplified assumption of a frozen lake, suitable for this high flow model.

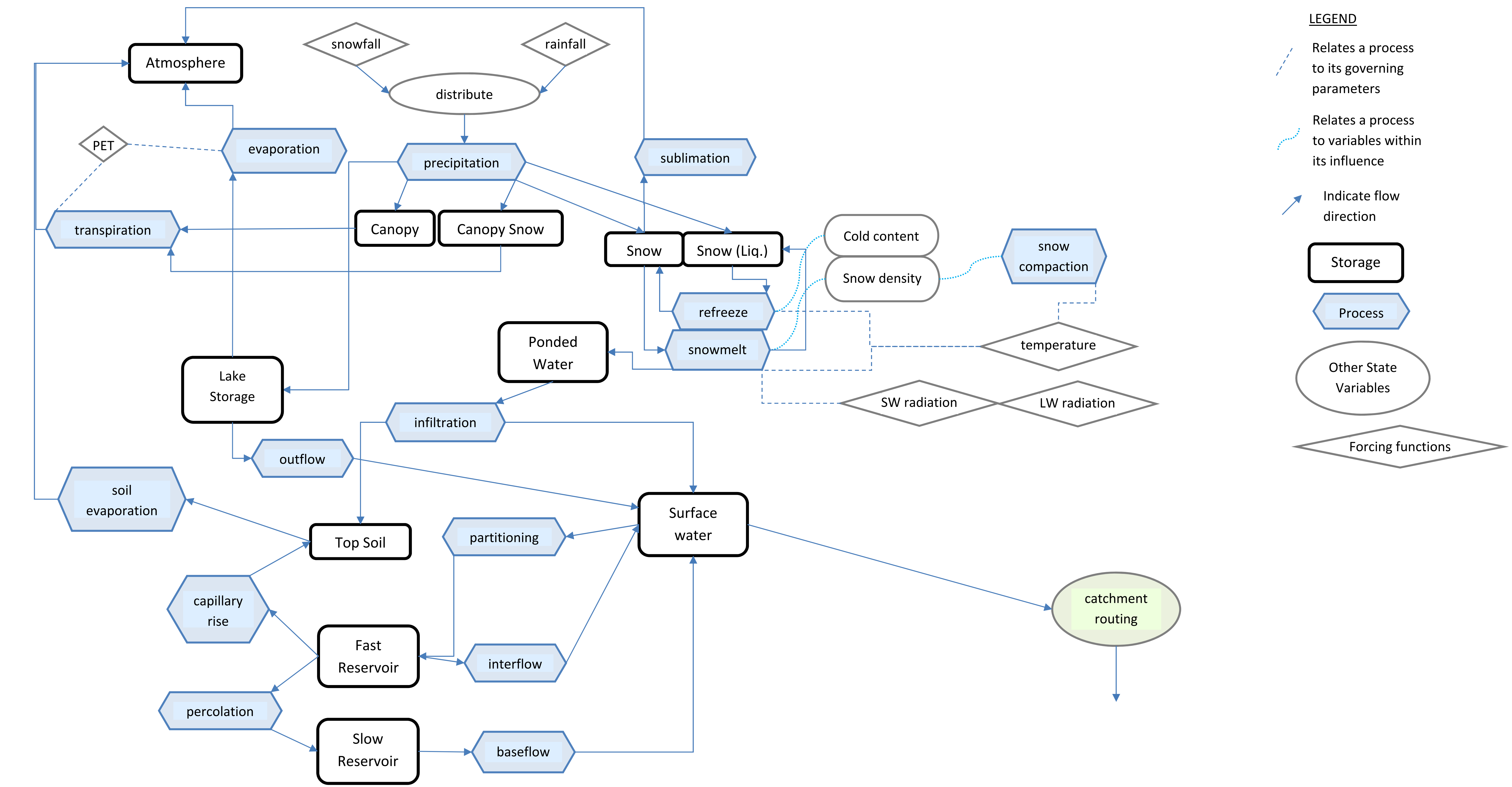


Figure 3 **Raven Model Schematic**

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.

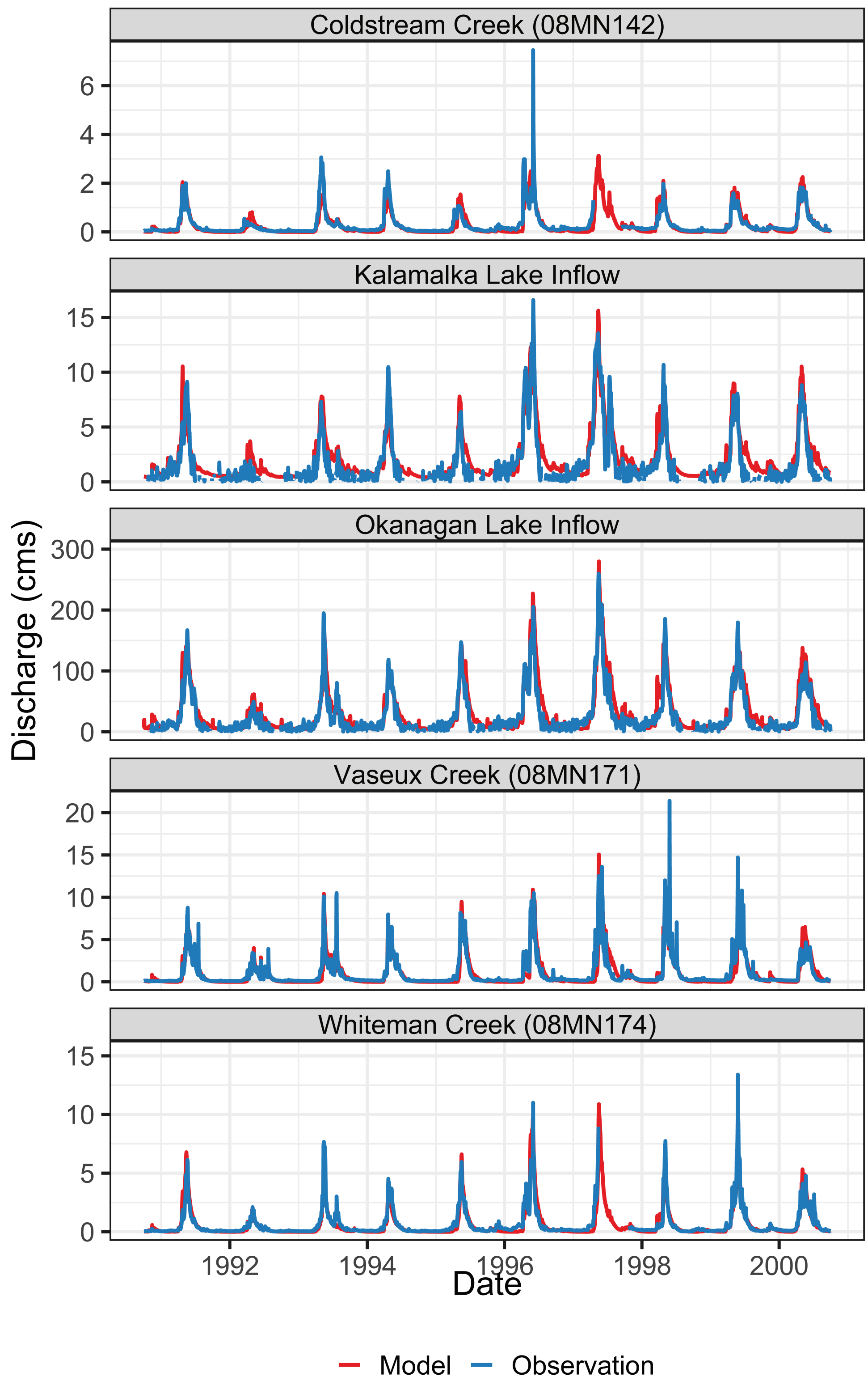


Figure 3-7 Calibration basins and Okanagan and Kalamalka Lake inflows (1990 - 2000).

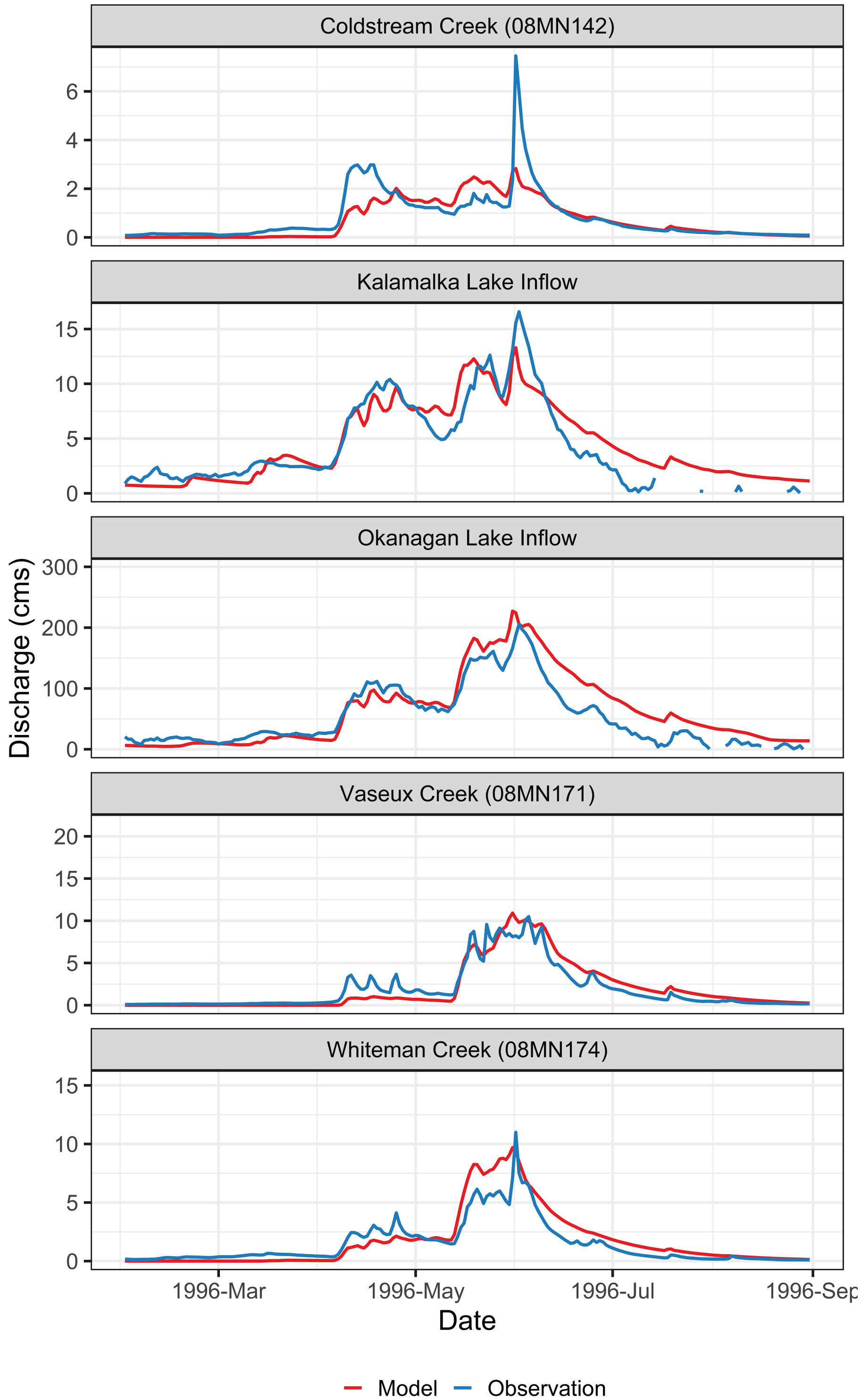


Figure 3-8 Calibration basins and Okanagan and Kalamalka Lake Inflows (Feb-1999 to Sep-1999). Note that observed (calculated inflows) include a 5-day rolling mean filter and removal of negative values to remove noise from calculations.

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.

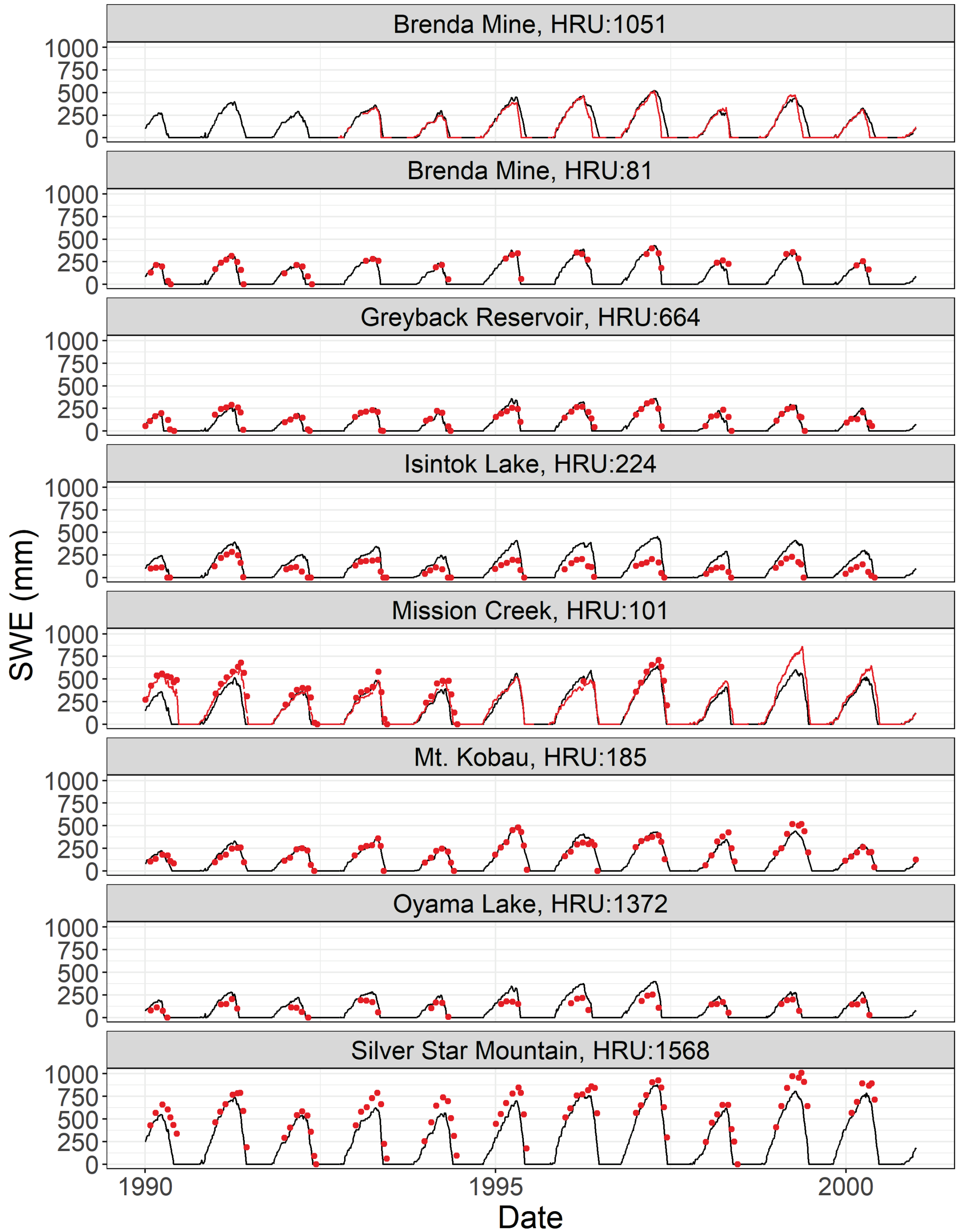


Figure 3-9 Snow model output for the middle calibration period. Red dots indicate manual snow surveys. Red lines indicate automated snow pillow output.

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.

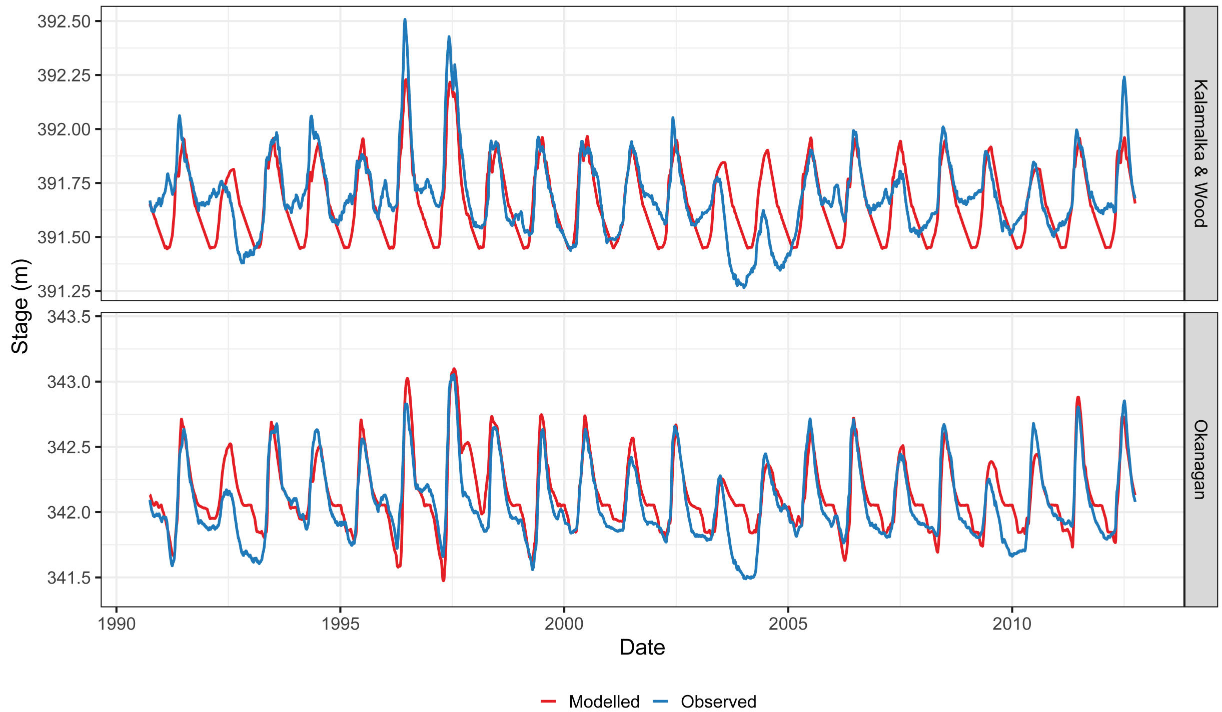


Figure 3-10 Calibrated lake stages at Okanagan Lake and Kalamalka/Wood Lake.

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.

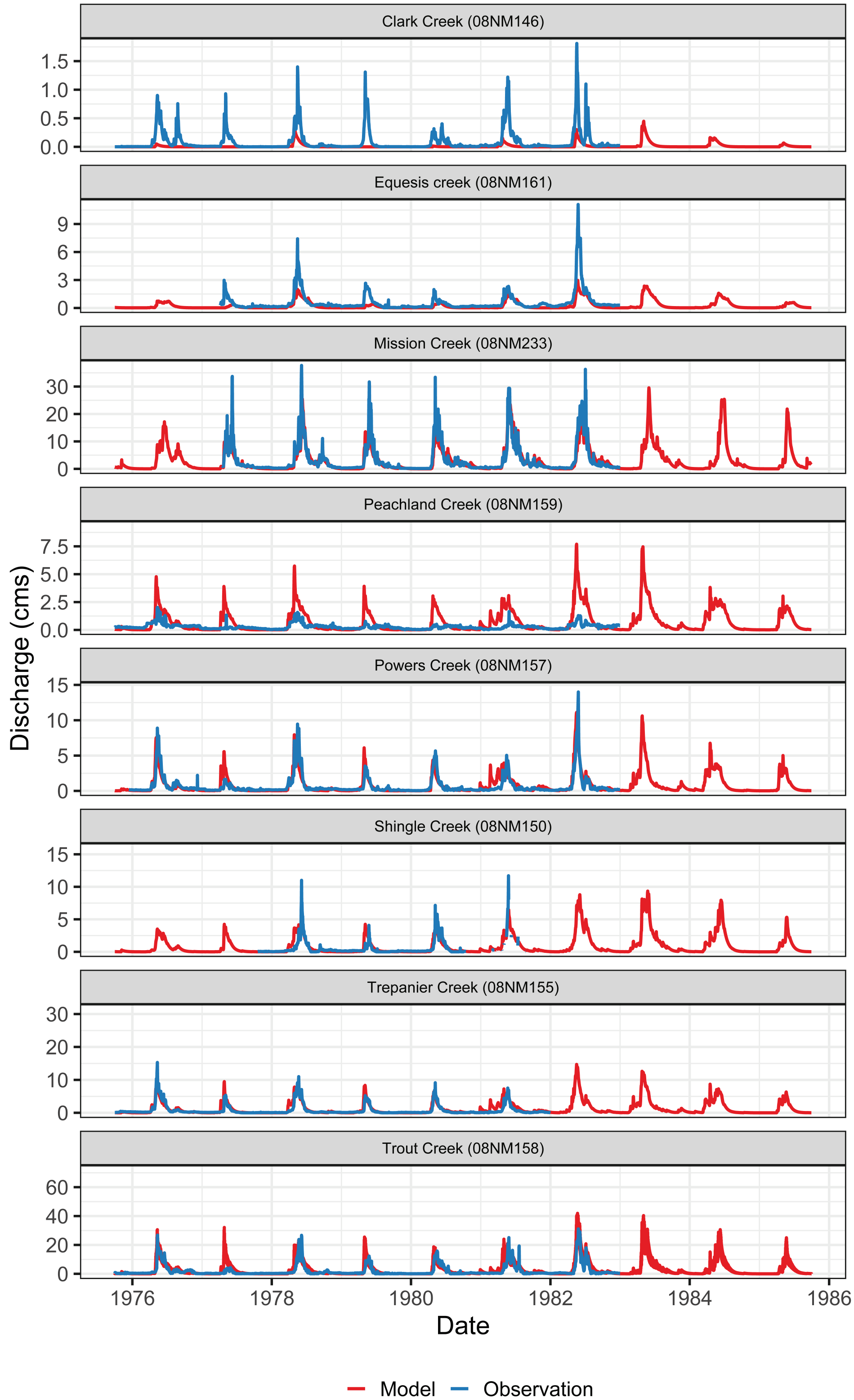


Figure 3-11 Select basins for spatial validation (1975 - 1985).

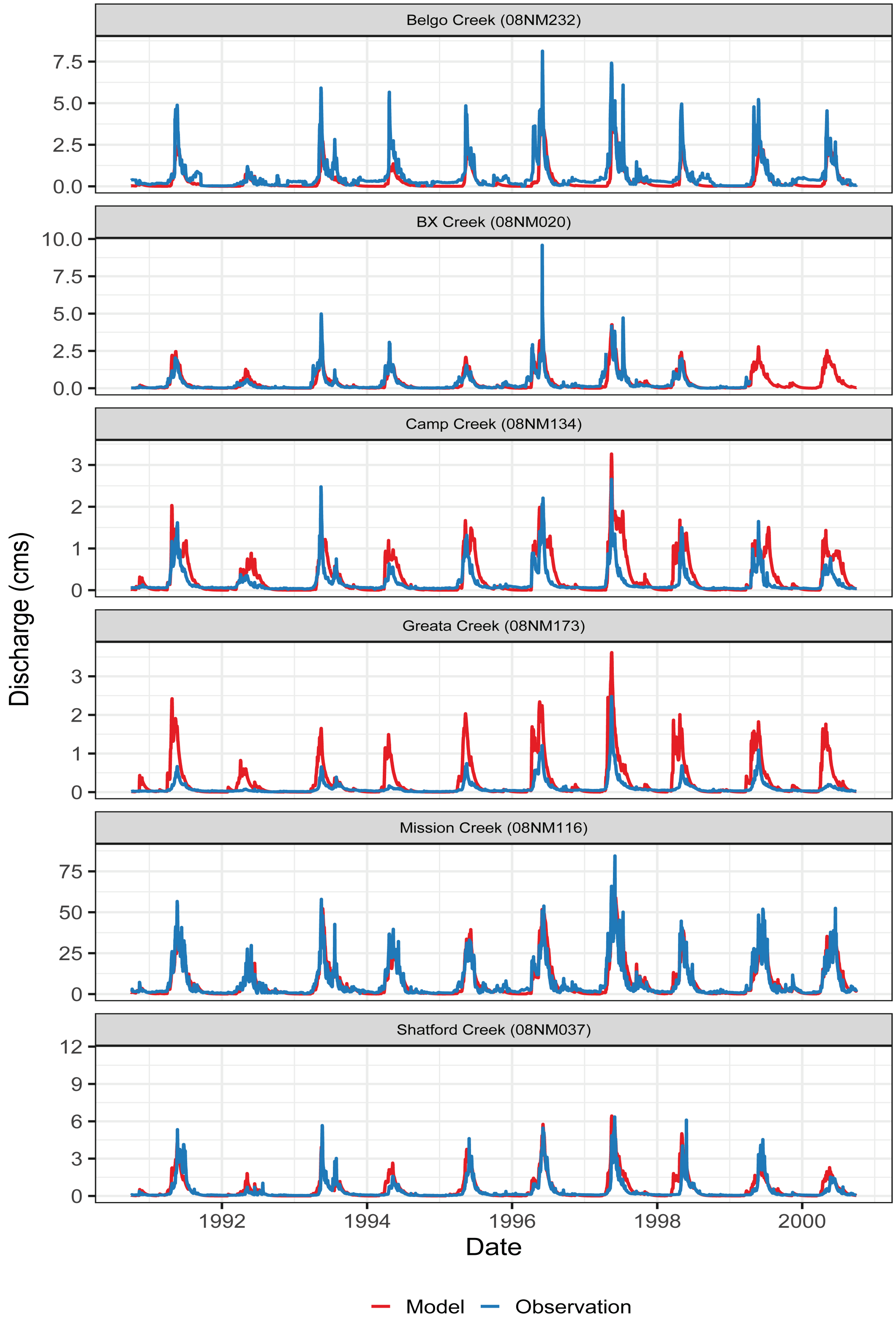


Figure 3-12 Select basins for spatial validation (1990 – 2000).

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.

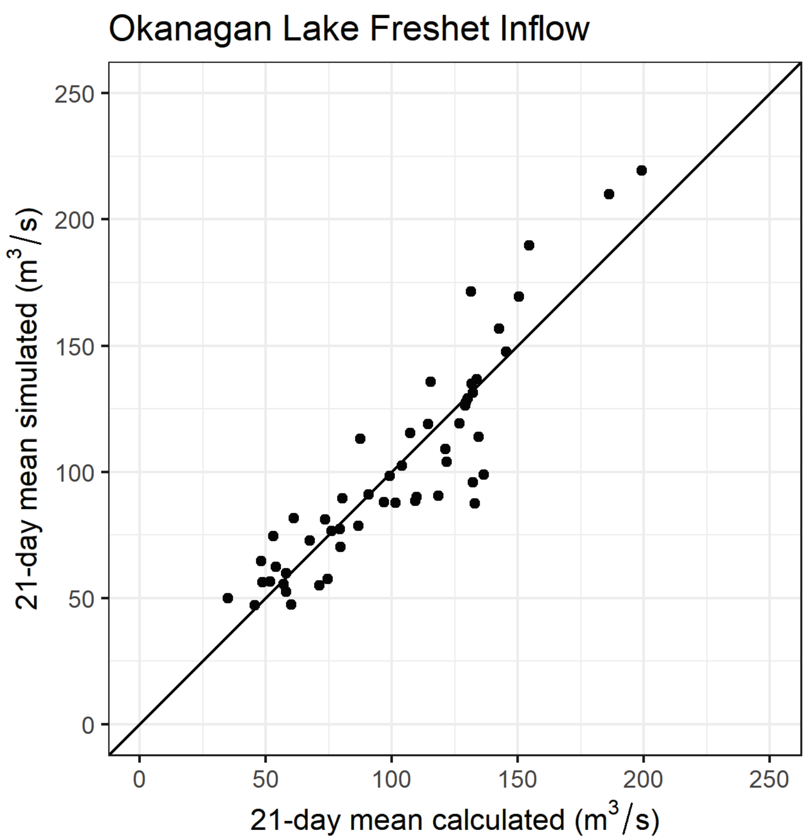


Figure 3-13 Comparison of calculated and observed Okanagan Lake inflow. Values indicate mean 21-day inflow, at the day of the peak +/- 10 days. Black line is a 1:1 line.

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.

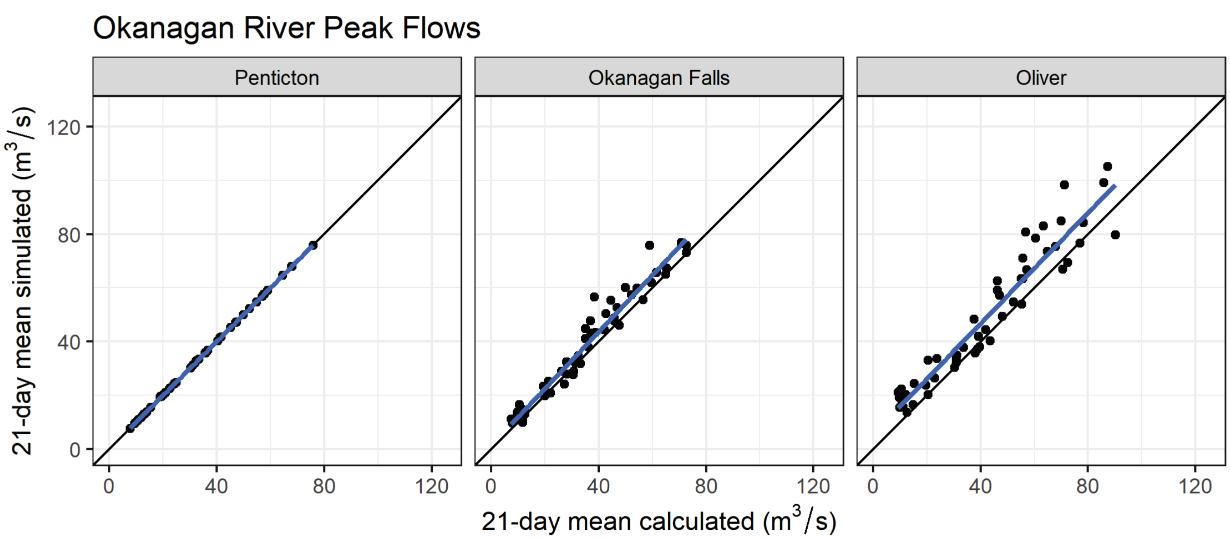


Figure 3-14 Comparison of calculated and observed Okanagan Lake River flows with observation override at Penticton. Values indicate mean 21-day inflow, at the day of the peak +/- 10 days. Blue lines are linear models of the data, black lines are 1:1 line.

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.

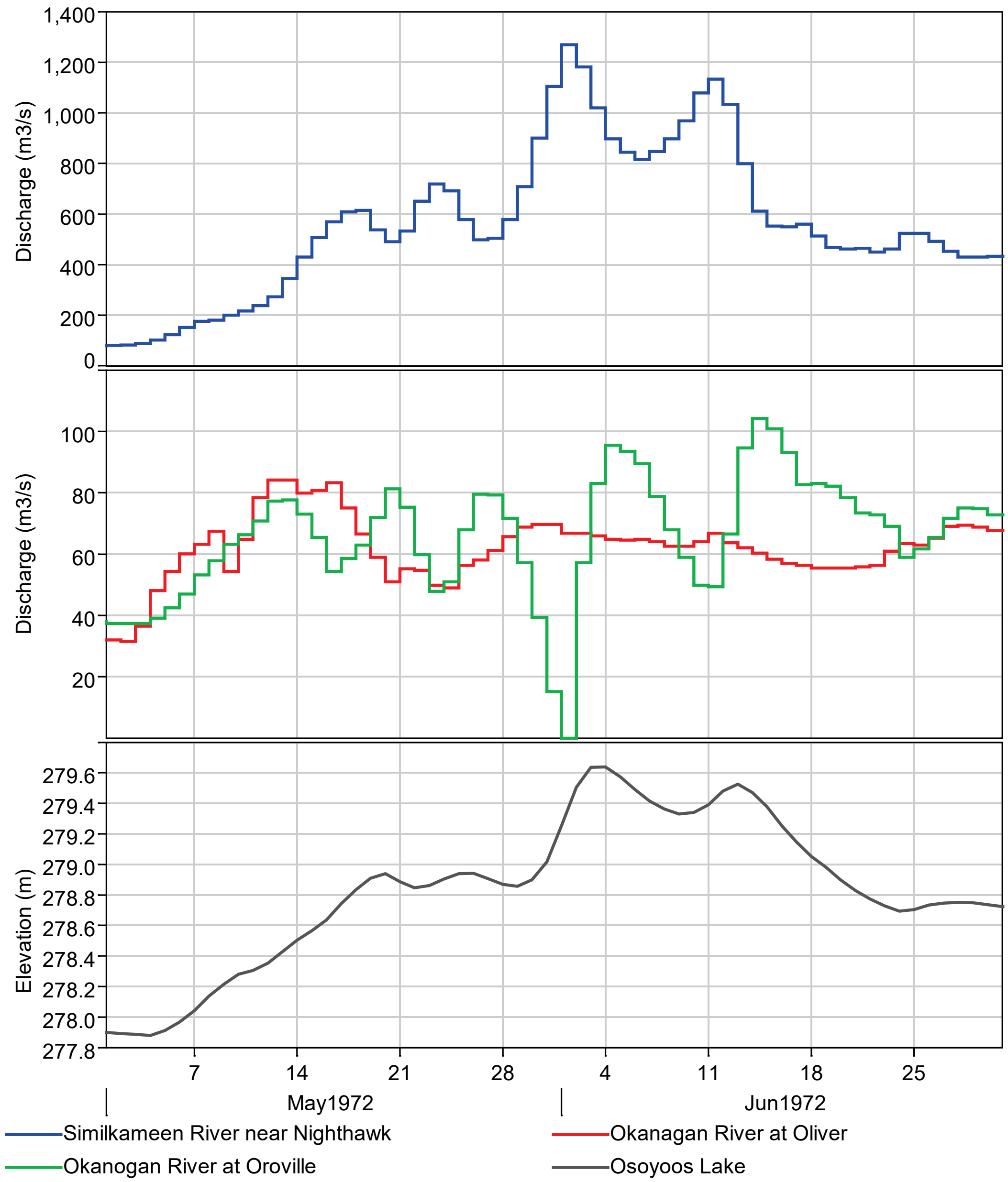


Figure 3-16 Illustration of backwater effects from high Similkameen River flows in the 1972 freshet.

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).

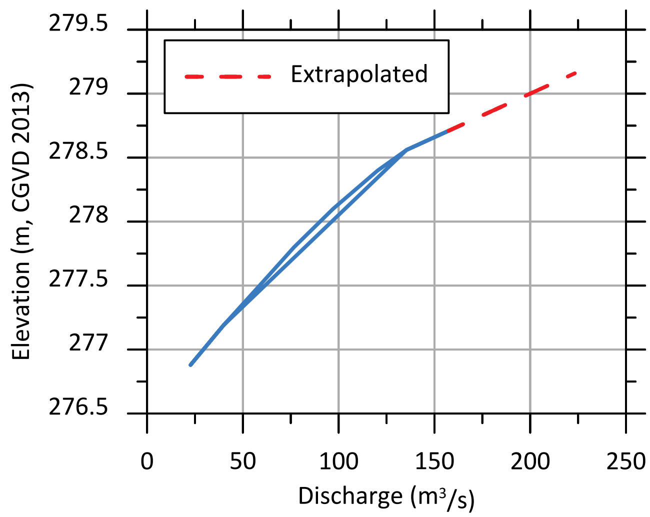


Figure 3-17 Osoyoos Lake elevation-discharge rating, Zosel Dam with gates fully open (adapted from Summit [2010]).

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.

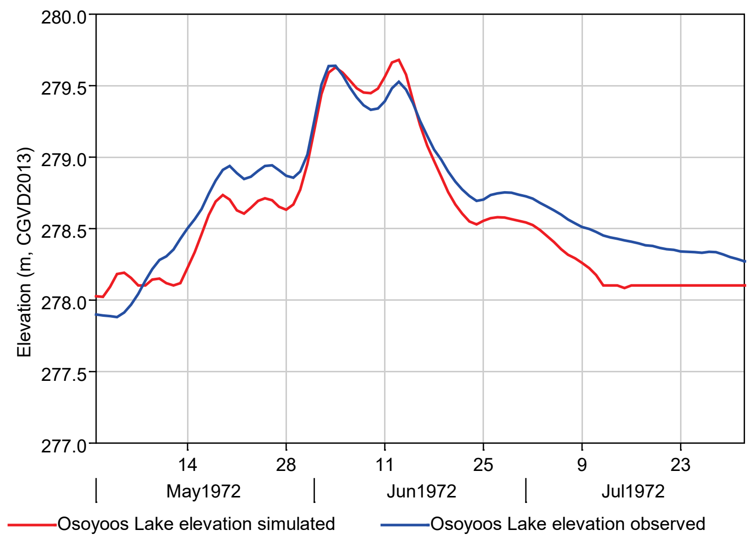


Figure 3-18 Simulated and observed Osoyoos Lake levels, May-July 1972. (Simulated based on observed Osoyoos Lake inflows and observed Similkameen River flows).

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.

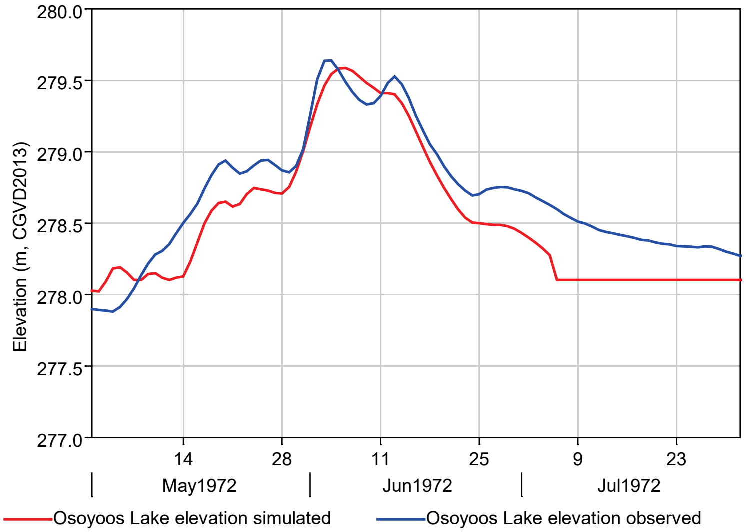


Figure 3-19 Simulated and observed Osoyoos Lake levels, May-July 1972. (Simulated based on observed Osoyoos Lake inflows and synthesized Similkameen River flows).

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.

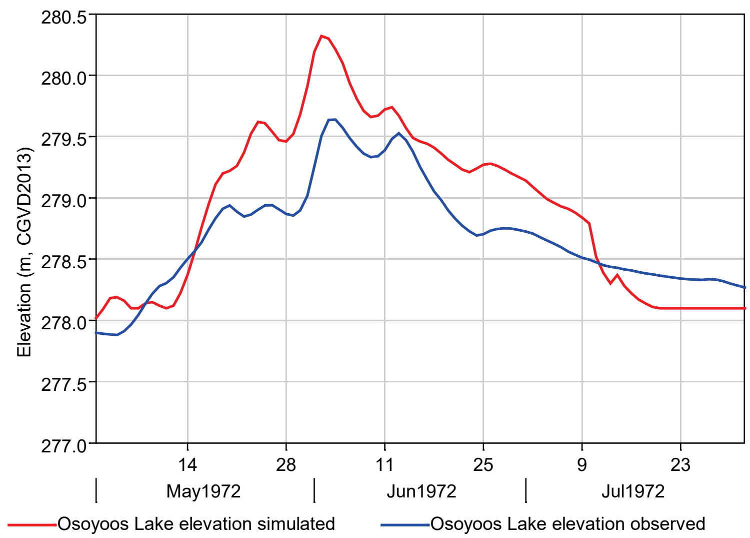


Figure 3-20 Simulated and observed Osoyoos Lake levels, May-July 1972. (Simulated based on simulated Osoyoos Lake inflows and observed Similkameen River flows).

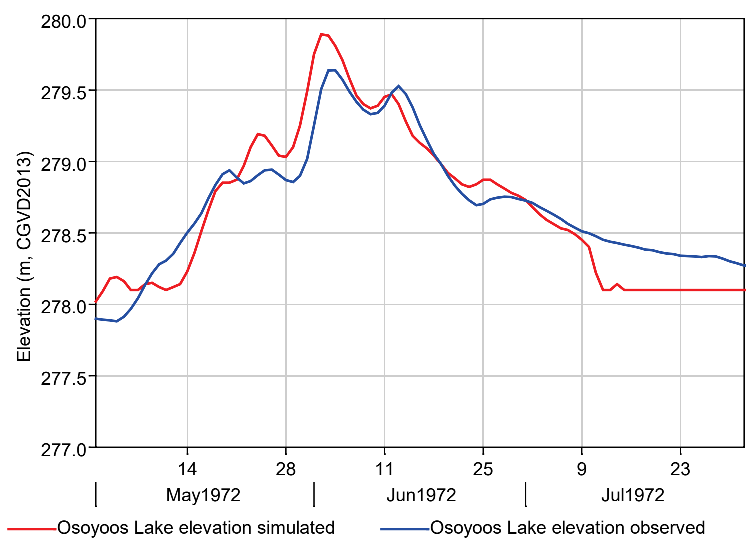


Figure 3-21 Simulated and observed Osoyoos Lake levels, May-July 1972. (Simulated based on bias-corrected simulated Osoyoos Lake inflows and observed Similkameen River flows).

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.

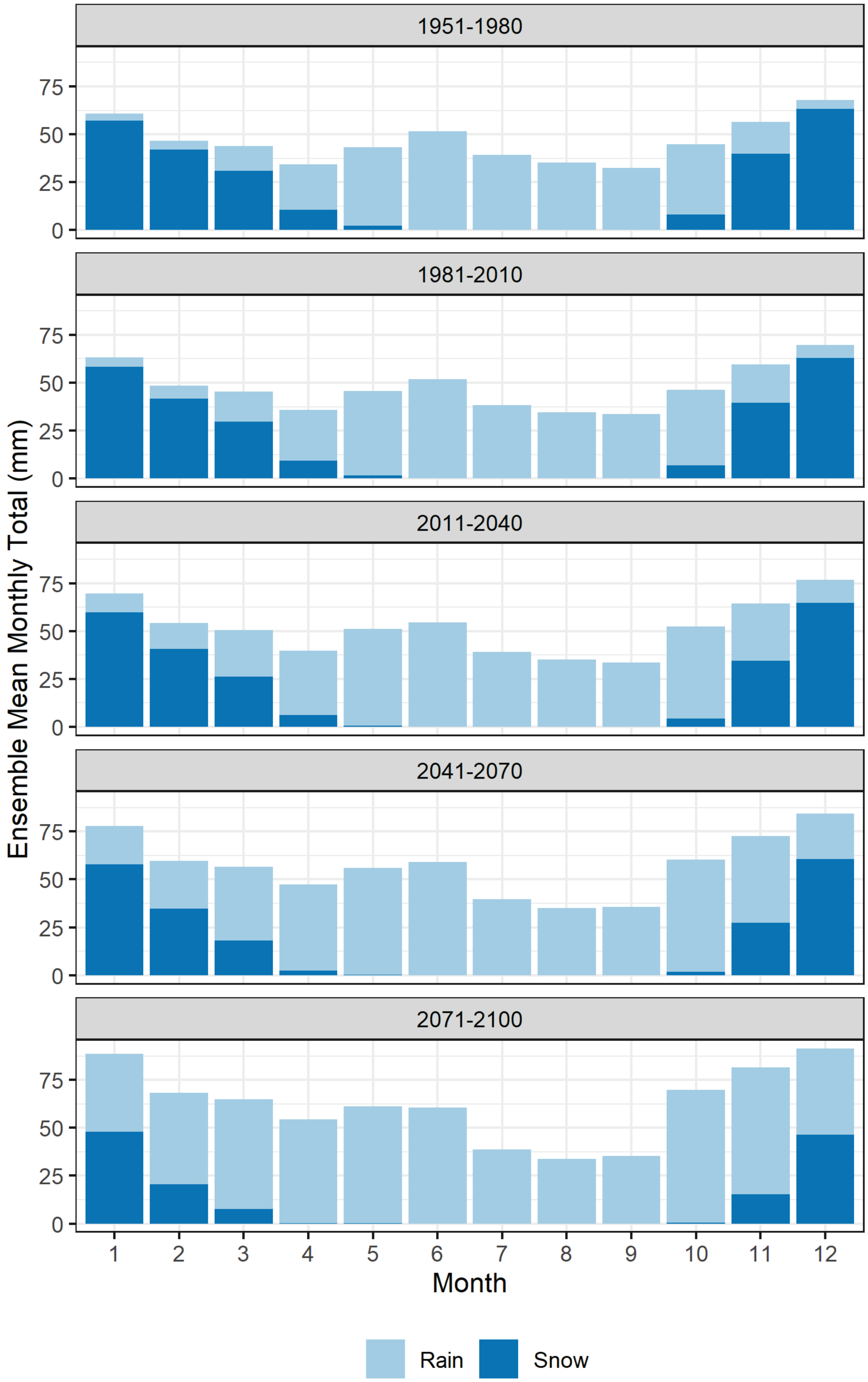


Figure 3-22 Mean monthly total precipitation by type (Snow or Rain) for the 50 ensembles.

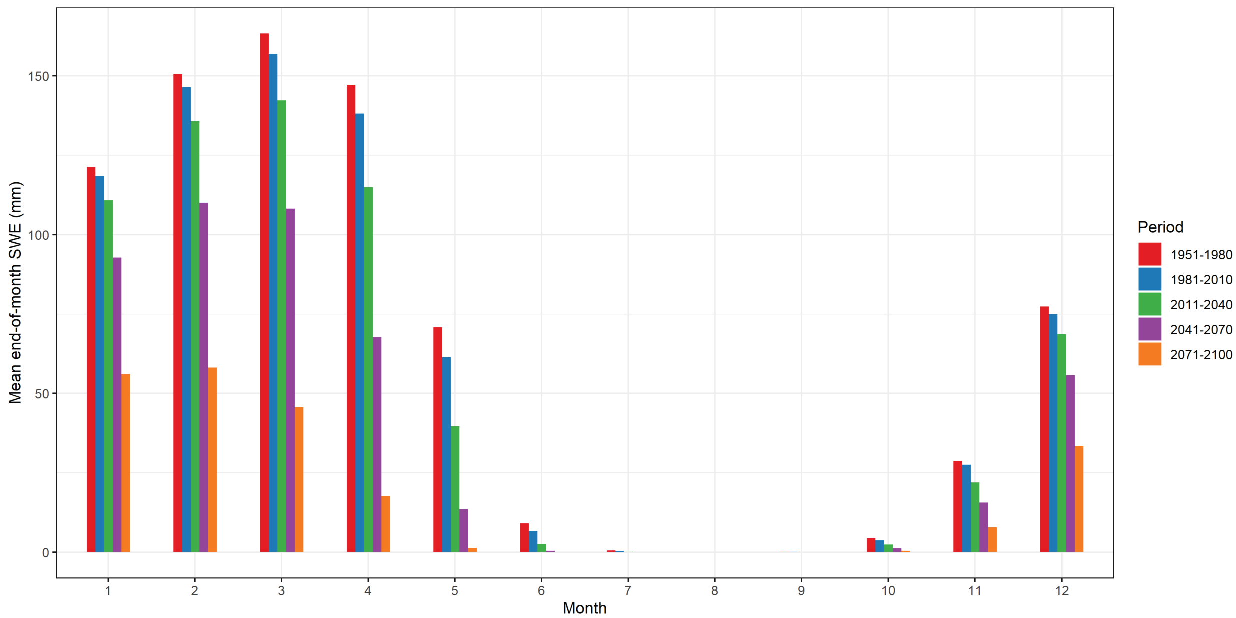


Figure 3-23 Mean end-of-the month SWE for the 50 climate ensembles averaged across the ORB.

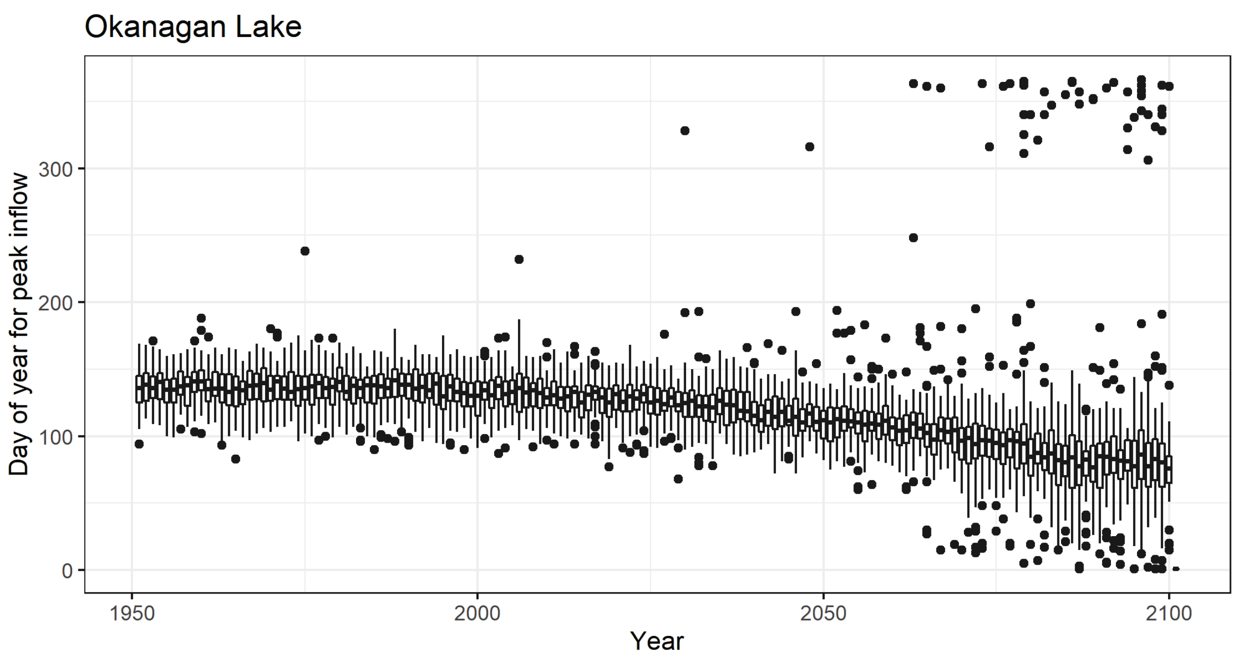


Figure 3-24 Timing of peak inflow date (shown as the day of the year) for ensemble simulation of Okanagan Lake. Each year is represented by a boxplot of the 50 ensemble members where the center line of the box is the ensemble median, the ends of the box represent the 25th and 75th percentiles, and outliers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

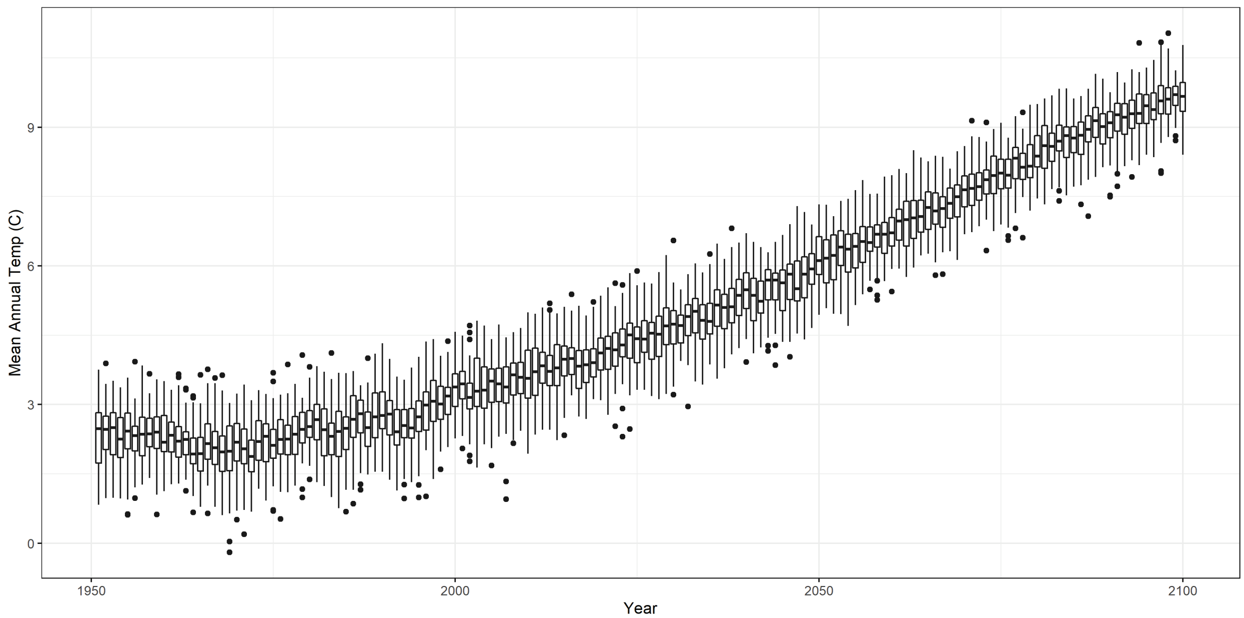


Figure 3-25 Mean Annual temperature at snow stations for 50 climate ensembles.

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 21^{st} 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.

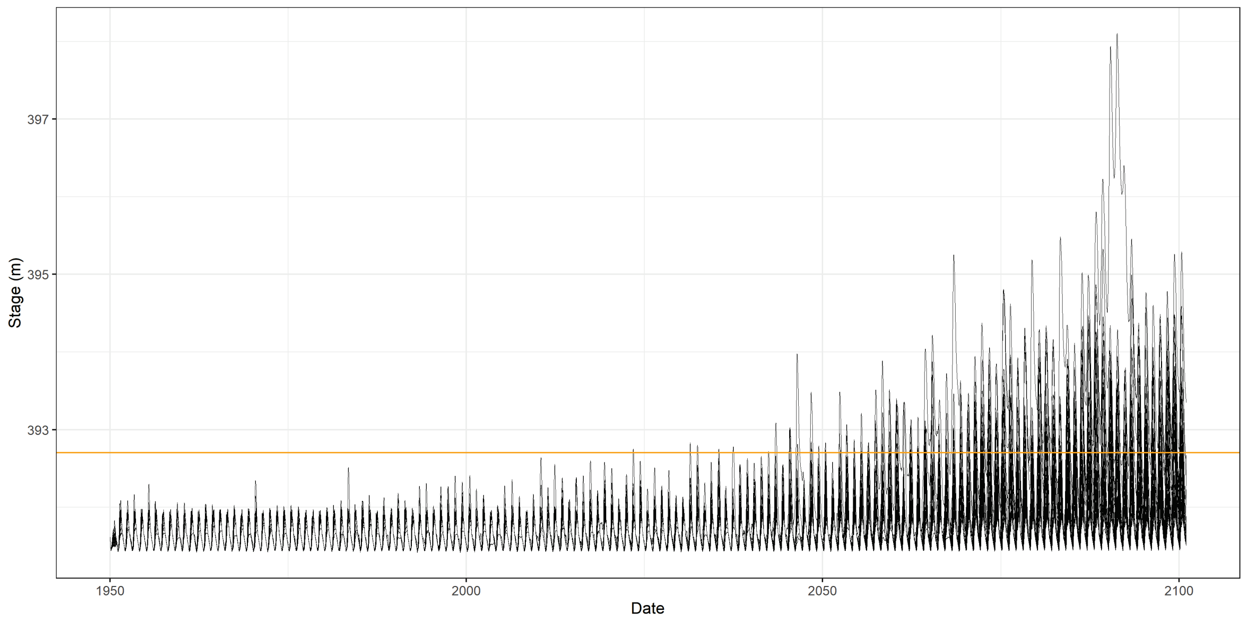


Figure 3-26 Lake levels at Kalamalka and Wood Lake from 1950 to 2100 for the present regulation scenario; orange line indicates 2017 maximum lake level.

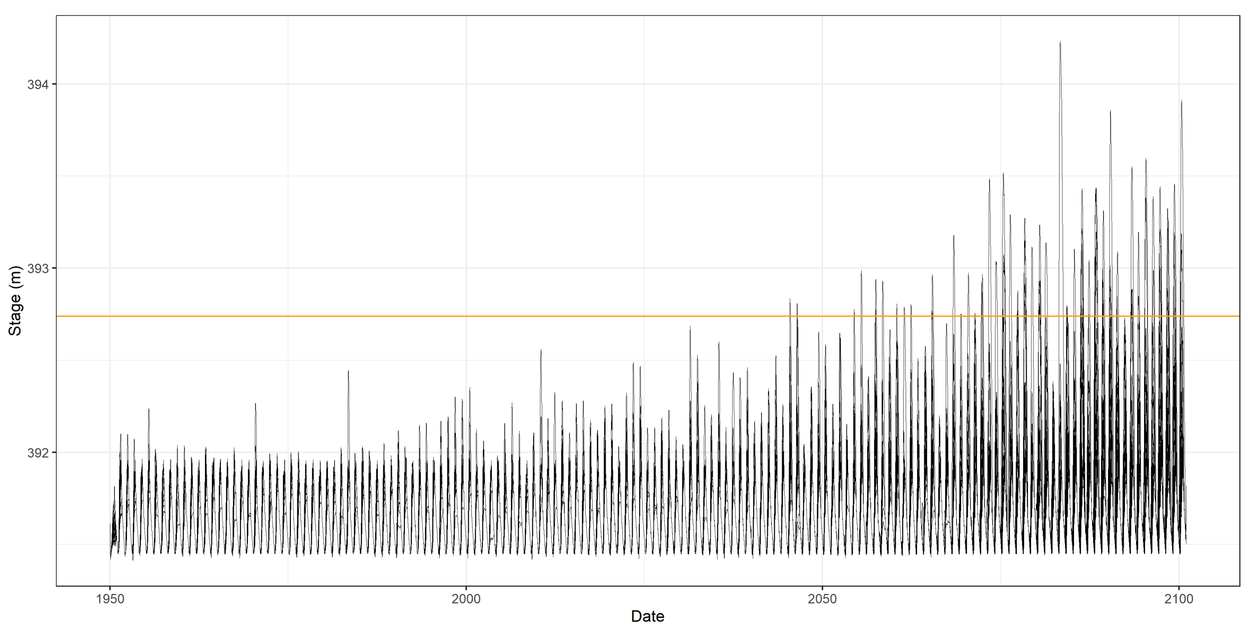


Figure 3-27 Lake levels at Kalamalka and Wood Lake from 1950 to 2100 for future regulation scenario; orange line indicates 2017 maximum lake level.

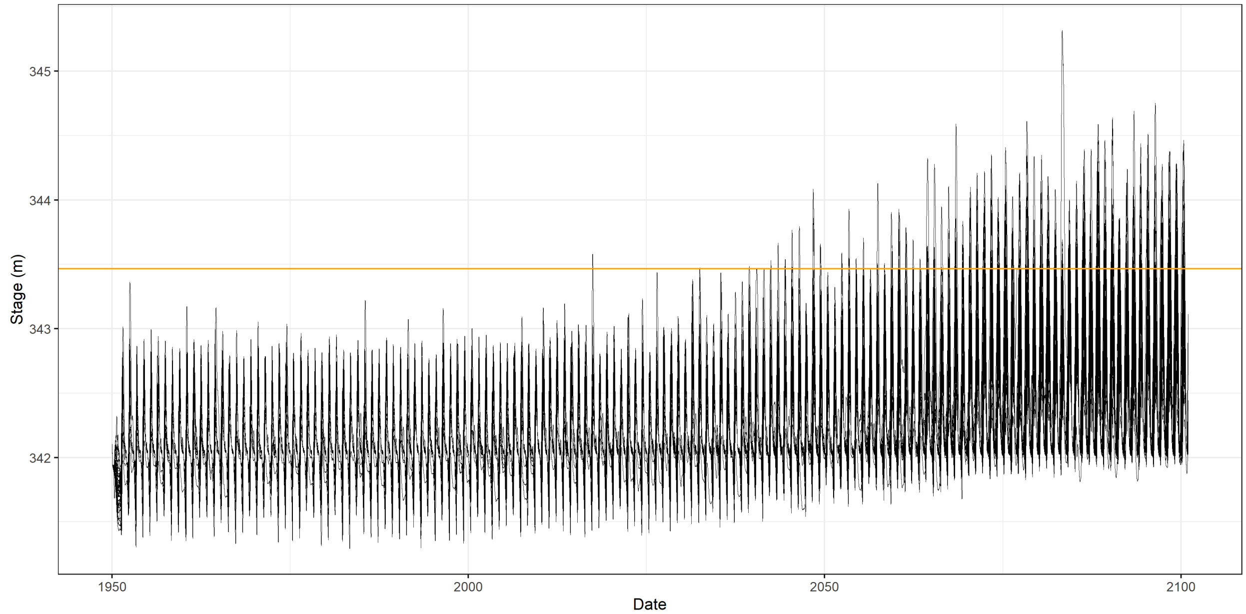


Figure 3-28 Lake levels at Okanagan Lake from 1950 to 2100 for the present regulation scenario; orange line indicates 2017 maximum lake level.

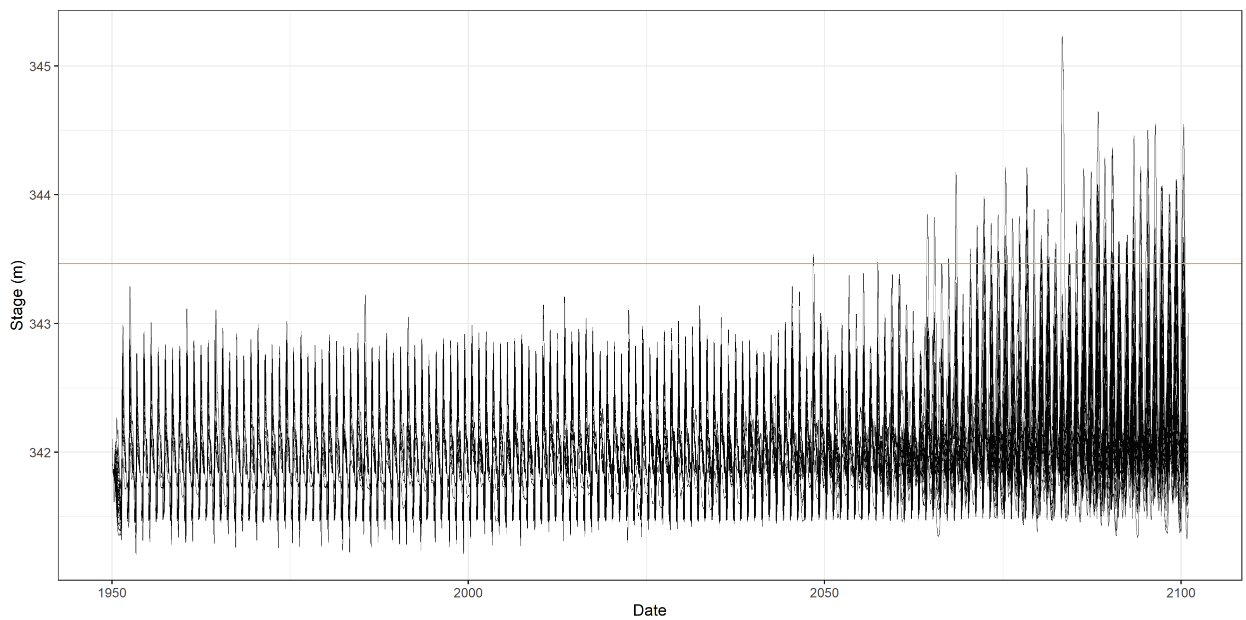


Figure 3-29 Lake levels at Okanagan Lake for the future regulation scenario from 1950 to 2100; orange line indicates 2017 maximum lake level.

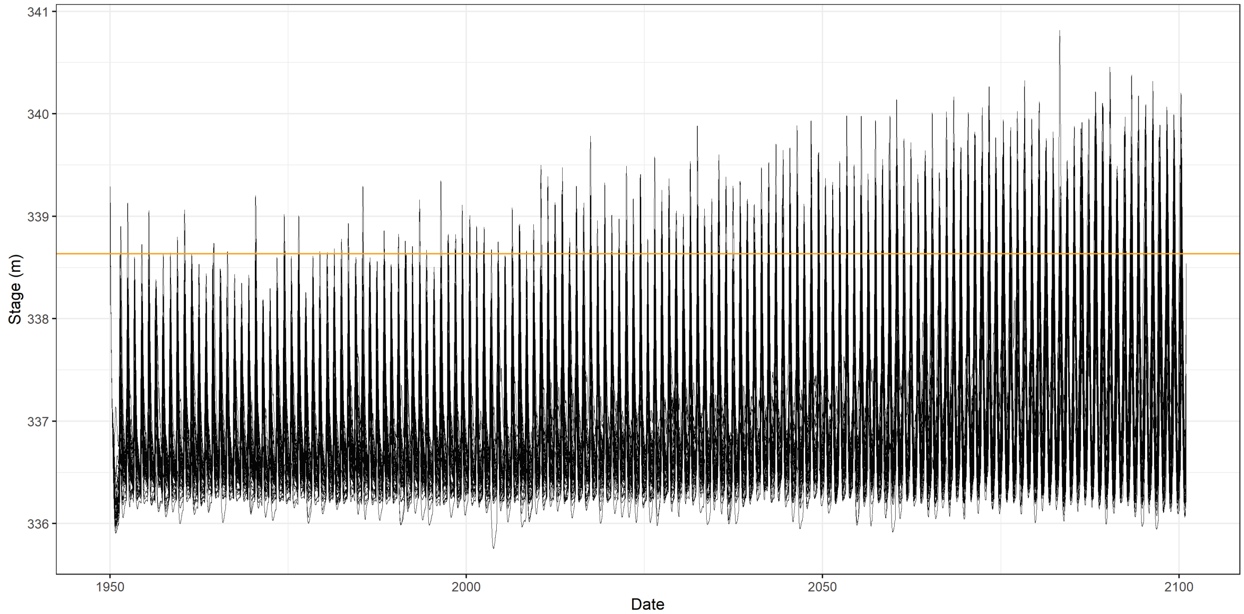


Figure 3-30 Lake levels at Skaha Lake from 1950 to 2100 for the gates open scenario; orange line indicates 2017 maximum lake level.

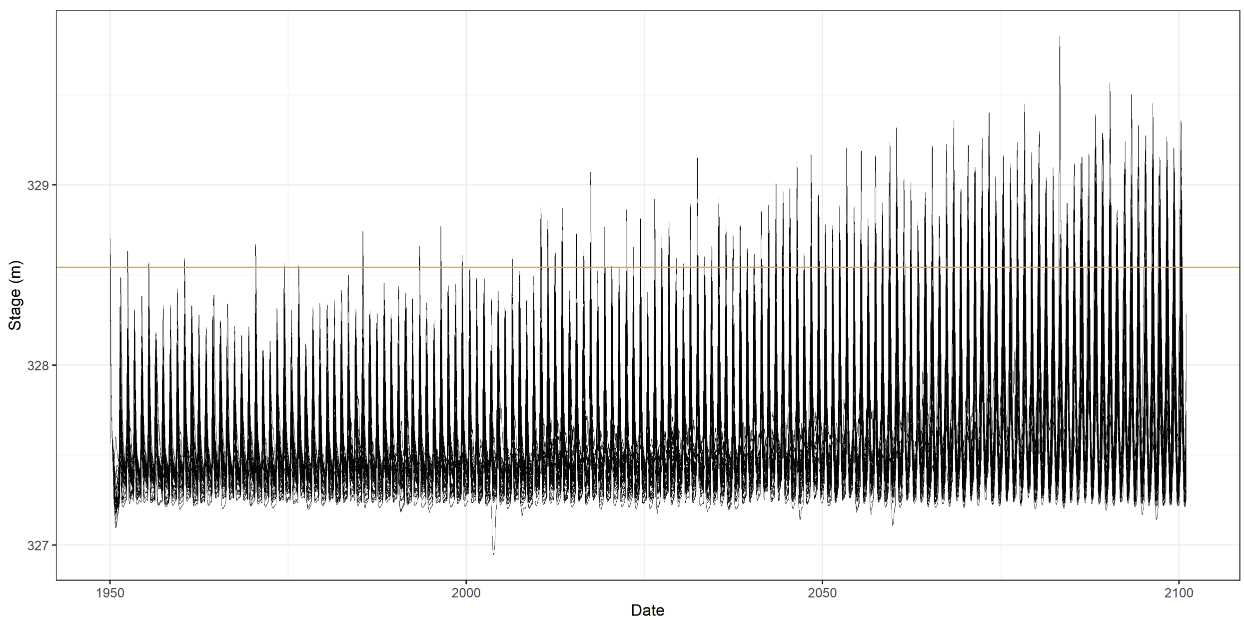


Figure 3-31 Lake levels at Vaseux Lake from 1950 to 2100 for the gates open scenario; orange line indicates 2017 maximum lake level.

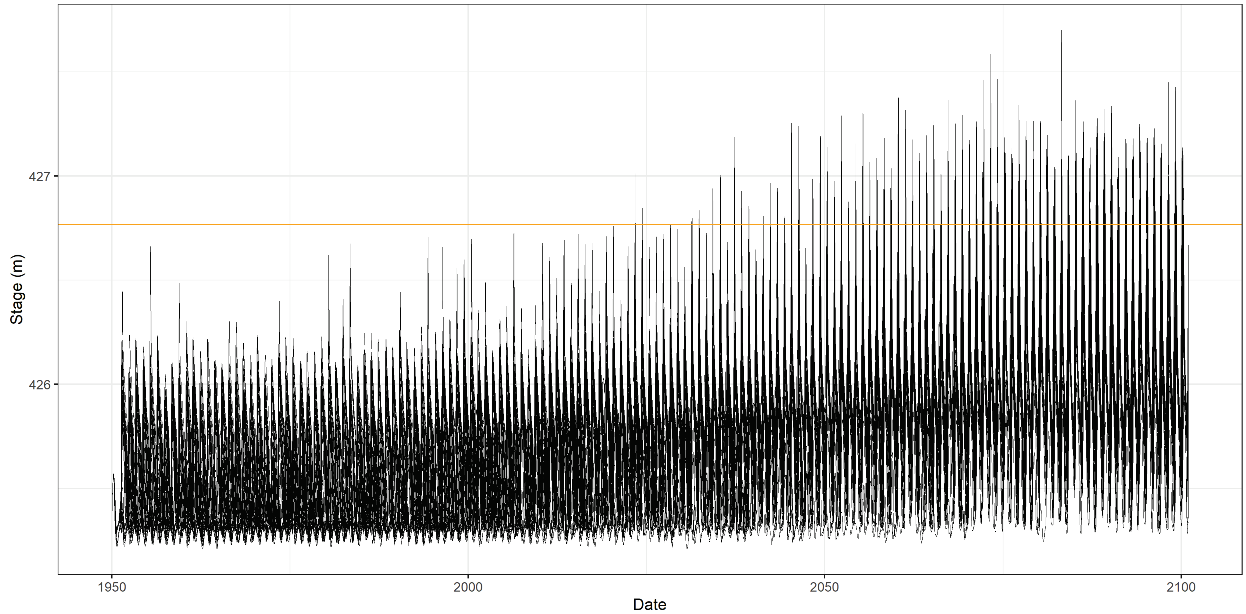


Figure 3-32 Lake levels at Ellison Lake from 1950 to 2100; orange line indicates 2017 maximum lake level (estimated from Lidar).

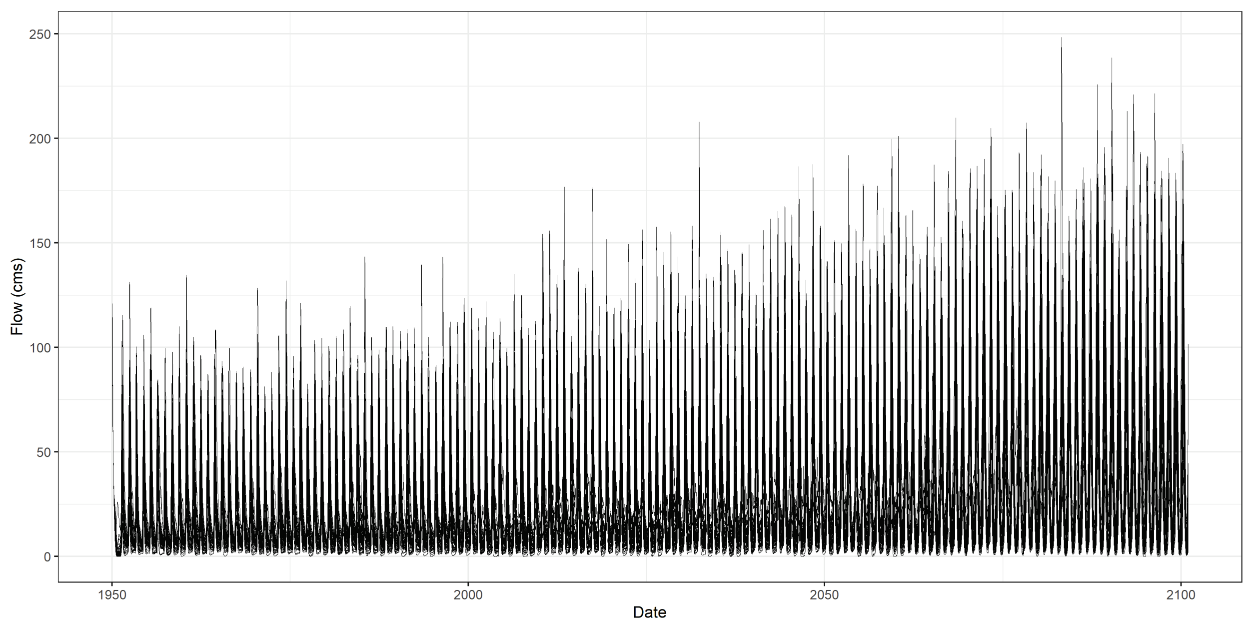


Figure 3-33 Daily discharge at Okanagan River at Oliver from 1950 to 2100 for Gates Open Scenario.

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].

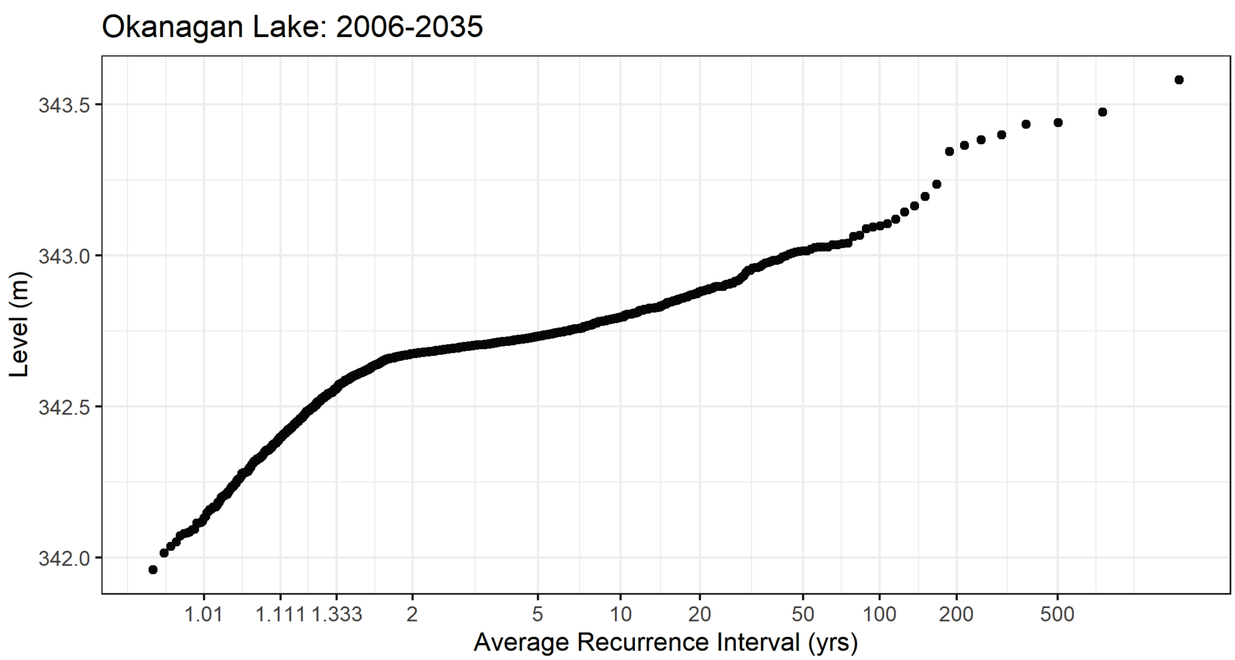


Figure 3-34 Empirical flood frequency analysis example for the 1500 years of simulation from 2006:2035 using the Weibull formula.

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.