Similkameen Basin Hydrologic Model
FINAL REPORT
Osoyoos Lake Climate Change Vulnerability Assessment (Phase 1)

Prepared by:

Northwest Hydraulic Consultants Ltd.
235 1 Avenue, #400
Kamloops, BC V2C 3J4
Tel: (250) 851-9262
www.nhcweb.com

NHC Project Contact:
Joel Trubilowicz, PhD, PEng
Environmental Data Scientist

March 31, 2021
Final Report, Rev. 1

NHC Reference 3005472

Prepared for:

International Joint Commission – International Osoyoos Lake Board of Control
234 Laurier Ave W., 22nd Floor
Ottawa, ON K1P 6K6

Document Tracking

Date	Revision No.	Reviewer	Issued for
2021-Mar-3	0		Client TAC review
2021-Mar-30	1	KML, PKK	Final

Report prepared by:

Sarah Grass, MASc, PEng
Water Resources Engineer
Project Engineer

Genevieve Brown, MASc, PEng
Hydrologist
Project Engineer

Dr. J. W. TRUSILOWICZ
47950
2021-3-31

Joel Trubilowicz, PhD, PEng
Environmental Data Scientist
Technical Lead

Report reviewed by:

Malcolm Leytham, PhD, PE
Principal Hydrologist
Senior Reviewer

2021.03.30
Piotr Kuraś, PEng, PE, RPF
Principal Hydrologist
Principal in Charge

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CREDITS AND ACKNOWLEDGEMENTS

The authors would like to thank the International Joint Commission – International Osoyoos Lake Board of Control for initiating this study and for the support provided during the project, in particular:

- International Osoyoos Lake Board of Control Canadian and US Secretaries
- IJC Technical Advisory Committee
- IJC – International Osoyoos Lake Board of Control Membership

Along with the authors and reviewers, the following NHC personnel participated in the study:

Rachel Managh	GIS Technician
Celeste Cameron, EIT	Junior Engineer

NHC partnered with Associated Environmental Consultants, Inc. (AE) on the Water Demand Estimation and Forecasting:

Drew Lejbak, MSc	Hydrologist, AE
Andras Szeitz, MSc, GIT	Environmental Scientist, AE
Lawrence Bird, MSc	Environmental Scientist, AE
Jeremy Fyke, PhD	Current: Environment Canada, Former: Climate Services, AE

FortisBC provided survey data for the Similkameen River near Hedley, BC:

Mujib Rahman, MEng, PEng	Senior Integrity Engineer - Geotechnical

EXECUTIVE SUMMARY

This report outlines Phase 1 of a study on the future of Osoyoos Lake water levels and operations by the International Joint Commission – International Osoyoos Lake Board of Control (IJC). The IJC uses the freshet (April 1 – July 31) flow volume on the Similkameen River (measured near Nighthawk, Washington) as an indicator for expected summer water levels on Osoyoos Lake. When the freshet flow volume is forecast to be less than 1 million acre-feet, drought operations on Zosel Dam – which controls low to moderate water levels in Osoyoos Lake – are enacted, allowing for a wider range of lake level operation throughout the summer.

The primary goal of this study was to determine if and how the frequency of drought operations is expected to change in the future. This goal was carried out first through the development and calibration of a semi-distributed hydrologic model using the Raven hydrologic modelling framework. After the model was constructed and calibrated, an ensemble of 50 climate projections (each containing daily maximum and minimum temperatures and daily total precipitation) was used to forecast potential changes in the hydrology of the watershed through the year 2100.

The Raven model development followed a framework developed by NHC in previous work on the adjacent Okanagan River Basin. A semi-distributed, daily timestep model was developed to strike a balance between hydrologic process realism and computational efficiency. Model calibration was performed using the model independent calibration tool Ostrich and focused on three main performance objectives: the Nash-Sutcliffe efficiency, the log Nash-Sutcliffe efficiency, and percent bias. Calibration results were strong, with a Nash-Sutcliffe efficiency of above 0.8 for both calibration and validation periods and no positive or negative bias for Similkameen River near Nighthawk, WA.

Modelling of climate projections with the calibrated model forecasted significant changes to the hydrology of the Similkameen River by the year 2100. The Similkameen River is forecasted to shift from a system dominated by the spring freshet, with low flows in winter and late summer, to a mixed hydrologic regime, with a diminished freshet, higher winter flows and lower late summer flows.

The 1 million acre-foot freshet threshold is expected to be triggered 40% of the time by the 2041-2070 future period and over 75% of the time in the 2071-2100 period. Late summer flow volumes are expected to gradually decrease, and the predictive ability of the freshet flows on the late summer flows is also expected to decrease.

The results of this study indicate that adaptations in both the seasonal forecasting for and operations of Osoyoos Lake should be re-evaluated. It is recommended that the following be explored: updated options for seasonal forecasting, and updated lake operations that potentially leverage the increase in winter flows.

TABLE OF CONTENTS

LIST OF TABLES IN TEXT

LIST OF FIGURES IN TEXT

APPENDICES

1 INTRODUCTION

The International Joint Commission (IJC) – Osoyoos Lake Board of Control are undertaking work to assess the long-term sensitivity of Osoyoos Lake to climate change. Osoyoos Lake is bisected by the international boundary between Canada and the United States, and hence is of interest to both nations. Water levels in Osoyoos Lake are influenced primarily by upstream inflows from the Okanagan River and outflow from Zosel Dam. However, during high water periods, the downstream outflow of the lake into the Okanogan River is hydraulically controlled by water levels at the confluence of the Similkameen River and Okanogan River.

Along with influence on lake levels during high water periods (e.g. the spring freshet), the Similkameen River plays an important role for Osoyoos Lake operations during lower flow periods. Zosel Dam is operated to maintain suitable lake levels for both Canadian and American residents, and to maintain water for environmental and agricultural use downstream on the Okanogan River during the summer. Because Osoyoos Lake and the Similkameen River are the primary water sources for summer baseflow on the Okanogan River, expected summer flows on the Similkameen River are an important criterion for Osoyoos Lake operations. When the April-July freshet flows on the Similkameen River near Nighthawk, Washington (WA) gauge (WSC – Water Survey of Canada: 08NL022 also named USGS – United States Geological Survey: 12442500) are forecasted (or observed) to be less than 1 million acre-feet, drought operations on Osoyoos Lake are enacted, allowing for a wider range of operating levels on Osoyoos Lake.

The primary goal of this study (Phase 1) is to investigate how the frequency of drought operating conditions is expected to change from the present through the end of the century (2100) due to projected changes in climate. This goal has been achieved through hydrologic modelling in the Raven hydrologic modelling framework (Craig et al., 2020) and subsequent ensemble hydrologic modelling with the calibrated model. Phase 2 will involve integration of the Similkameen hydrologic model with a previously developed hydrologic model of the Okanagan basin (NHC, 2020) to complete the assessment of the impact of projected climate change on Osoyoos Lake.

1.1 Study objectives

The primary objectives of Phase 1 of the Osoyoos Lake Climate Change Vulnerability Study include:

- Development and calibration of a hydrologic model of the Similkameen basin using the Raven Hydrologic Modelling Framework (Craig et al., 2020) in a manner consistent with the previously developed Okanagan basin model (NHC, 2020).
- Simulation of historic and projected future flows of the Similkameen basin to analyse the April to July drought criteria for the Similkameen basin.

1.2 Project area

The Similkameen Basin is located across British Columbia and Washington, with a total contributing area of 9,273 km^2. The basin ranges from an elevation of 276 m at its confluence with the Okanogan[1] River to over 2,000 m in the Cascade mountains (Obedkoff, 1973). A hypsometric curve of the basin is shown in Figure 1.1. In comparison to the Okanagan basin, the Similkameen Basin is not highly regulated; however, there are some lakes which provide storage within the basin (Issitz Lake, Palmer Lake, Wolfe Lake, and Missezula Lake) and some degree of regulation (Otter Lake). The basin is sparsely populated and the largest population centre is Princeton (estimated population of 2,800 people), located in the centre of the basin. Despite the sparse population, there is still substantial water licensing, primarily due to agriculture in the lower elevations of the basin and some mining (e.g. Copper Mountain mine, 10km south of Princeton).

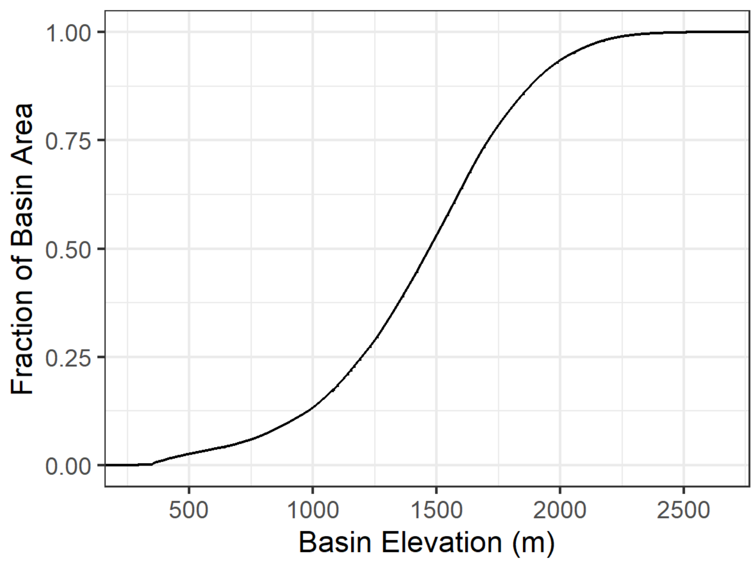

Figure 1.1 Hypsometric curve of Similkameen Basin

The presence of the Cascade mountains in the west creates two distinct hydrologic zones within the basin, a western wet zone and an eastern semi-arid dry zone (Obedkoff, 1973). Average annual precipitation ranges from 350 mm to over 1200 mm, depending on the location within the basin. At the outlet of the Similkameen Basin, the hydrograph is largely dominated by the freshet in May and June with recession in July and August (Figure 1.2). Mean annual discharge at the outlet (WSC 08NL022) is 65 m^3/s with a mean annual flood of 465 m^3/s and the average annual 7-day low flow is 9 m^3/s.

[1] Okanagan = Canadian spelling, Okanogan = American spelling.

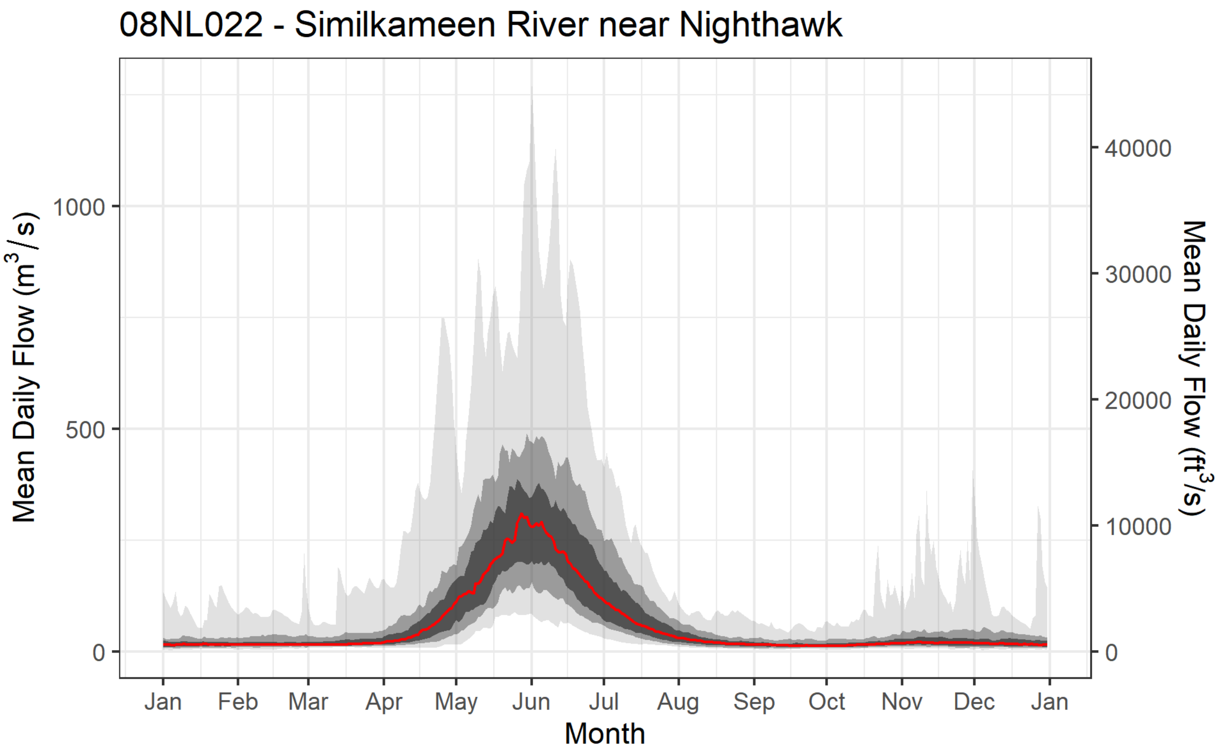

Figure 1.2 Similkameen River near Nighthawk, WA hydrologic regime. Red line represents median flow (1928-2018), grey bands represent 25th-75th percentile, 10th-90th percentile, and maximum/minimum, respectively according to shade.

1.2.1 Prior research

Peak flows occur primarily during the spring freshet, with the most extreme events enhanced by spring rainfall on an already melting snowpack. However, fall peak flows have occurred and are most likely driven by rainfall in the western portion of the basin on top of a thin, early season snowpack. Leith and Whitfield (1998) found that a detectable trend towards increasing winter flows (e.g. a change of hydrologic regime) has been evident on the streamflow records of the Similkameen River as far back as the mid 1990s. However, Jain and Lall (2001) found that the magnitude of peak flows on the Similkameen River are also related to climate indices, such the El-Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). They found that larger annual peak flows are favored in years with negative PDO and ENSO anomalies (i.e. cool phases).

Disentangling the influences of annual or decadal climate variation (e.g. PDO and ENSO) from the long term changes due to climate change is a primary goal of the hydrologic modelling undertaken in this study. A conceptual understanding of the watershed and predicted climate change in the area indicates that warming temperatures will lead to smaller winter snowpacks and earlier melt. Hydrologic and groundwater modelling on the nearby Kettle and Granby Rivers (Scibek et al., 2007) has indicated that this earlier melt led to quicker baseflow recession and a shift from groundwater recharge to groundwater discharge earlier in the summer.

Hydrologic modelling across the Pacific Northwest has indicated that the impact of climate change on summer low flows depends on the moisture in the basin. Vano et al. (2014) found that changes in low flows were most pronounced in higher moisture watersheds near the Pacific coast. Drier interior watersheds in the region (e.g. watersheds that are water stressed at the present time) did not show pronounced decreases in summer low flows. The authors hypothesized that this is due to the coastal watersheds having more water to lose in summer periods, whereas interior watersheds are already nearly drying out in summer, and hence could not become notably drier in a warmer future.

Results such as these and NHC's recent hydrologic modelling for the Okanagan Basin (NHC, 2020), could be extrapolated to the Similkameen River. However, the specific results (such as peak flows, freshet timing, annual water yield and low flows) for the Similkameen River are the result of a balance of competing factors in climate inputs and hydrologic processes. For example, it is unknown how the balance between more total precipitation (a positive driver on annual water yield) will be counteracted by increasing temperatures and hence evapotranspiration (a negative driver on annual water yield) without site-specific hydrologic modelling. Thus, hydrologic modelling applied directly on the Similkameen River is the most appropriate method for analysing these potential changes.

2 MODEL DEVELOPMENT

This section describes how the Raven hydrologic model was developed for the Similkameen Basin. The model was developed largely in a similar manner to NHC's Okanagan Basin Raven model (NHC, 2020); situations where differences occurred are noted in the text.

2.1 Collection and preparation of input data

2.1.1 Meteorological forcing data

The hydrologic model forcing variables (daily maximum and minimum temperature and daily total precipitation) were obtained in gridded format from an Okanagan-Similkameen gridded meteorological dataset in a 500 m x 500 m grid for the years 1945-2012. The gridded dataset was originally created by Associated Environmental, Inc. (Associated Environmental, 2019) for use in the development of the Raven model of the Okanagan Basin (NHC, 2020). The 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 (Werner et al., 2019) and a 500 m spatial resolution monthly climatology surface 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) using software developed in the statistical programming language 'R' (Hornik, 2016). The HRU is the smallest spatial discretization represented within the Raven model, described in Section 2.3.1. Total precipitation data was partitioned into rain and snow using the precipitation partitioning equation from the HBV[2] hydrologic model (Bergstrom, 1995).

2.2 Hydrologic data

Three sources of data were used to calibrate and validate the model: hydrometric data, snow survey data, and evapotranspiration data. Hydrometric data was used for hard calibration (i.e. calibration using formalized model optimization) while evapotranspiration and snow data were used for soft calibration (i.e. manual investigation of realistic internal model representation).

A total of 16 hydrometric gauges, operated by the Water Survey of Canada (WSC) and the United States Geological Survey (USGS), were used to inform the model development. Nine of these gauges were used for the primary calibration and validation. Four were used as secondary validation to exploit the amount of information available to inform the model. Stage data from three lakes within the basin were used in the model calibration. Table 2.1 provides a summary of all hydrometric data, and Figure 2.1 shows the spatial locations within the Similkameen Basin.

[2] Hydrologiska Byråns Vattenbalansavdelning

Table 2.1 Hydrometric data used for model development and calibration.

Gauge ID	Gauge Name	Drainage Area (km^2, mi^2)	Period of Record	Data Type[1]	Data Role
12442500 08NL002	Similkameen River near Nighthawk, WA	9194, 3550	1928-2020	Q	Calibration and Validation
08NL004	Ashnola River near Keremeos	1050, 405	1912-2020	Q	Calibration and Validation
08NL007	Similkameen River at Princeton	1810, 699	1914-2020	Q	Calibration and Validation
08NL024	Tulameen River at Princeton	1780, 687	1950-2020	Q	Calibration and Validation
08NL038	Similkameen River near Hedley	5580, 2155	1965-2020	Q	Calibration and Validation
08NL050	Hedley Creek near the mouth	388, 150	1973-2020	Q	Calibration and Validation
08NL069	Pasayten River above Calcite Creek	566, 219	1974-2020	Q	Calibration and Validation
08NL070	Similkameen River above Goodfellow Creek	408, 158	1973-2020	Q	Calibration and Validation
08NL071	Tulameen River below Vuich Creek	253, 98	1974-2020	Q	Calibration and Validation
12442000	Toats Coulee Creek near Loomis, WA	337, 130	1920-1970	Q	Secondary Validation
12442300	Sinlahekin Creek above Chopaka Creek near Loomis, WA	663, 256	1957-1965	Q	Secondary Validation
08NL036	Whipsaw Creek below Lamont Creek	185, 110	1964-1999	Q	Secondary Validation
08NL060	Otter Creek below Spearing Creek	409, 158	1973-1982	Q	Secondary Validation
08NL041	Wolfe Creek at outlet of Issitz Lake	215, 83	1968-1981	WL	Secondary Validation
08NL043	Summers Creek at outlet of Missezula Lake	123, 47	1970-1980	WL	Secondary Validation
08NL023	Otter Creek at Tulameen	673, 298	1912-1985	WL	Secondary Validation

Notes:
1. Primary data type, either Discharge (Q) or Stage (WL)

Automated and manual snow survey data, provided by the BC Ministry of Environment and Climate Change Strategy Snow Survey Program and the USGS, were used as a soft calibration target for assessing the snow accumulation and melt routines, and as an indirect method for assessing the quality of the precipitation inputs at high elevations. A total of 11 sites were used as summarized in Table 2.2.

Evapotranspiration is a critical component of the water cycle in the Similkameen, but data was not available in timeseries format (and rarely is); however, we were instead able to compare modelled annual evapotranspiration with the estimated value of 410 mm/year for 1981 to 2010 for the Okanagan-Similkameen Basin (Statistics Canada, 2017).

Kelowna
Peachland Lake
Okanagan Lake
Summerland
Penticton
Skaha Lake
Vaseux Lake
Oliver
Osoyoos Lake
Osoyoos
Oroville
Zosel Dam
MODEL END
Palmer Lake
08NL060
Missezula Lake
08NL043
Missezula Mountain
Trout Creek
Otter Lake
08NL023
Hamilton Hill
08NL071
08NL024
08NL007
Princeton
Similkameen River
Copper Mountain
08NL041
08NL036
Smelter Lakes
Sunday Summit
08NL038
Nickel Plate
08NL050
Lost Horse Mountain
08NL004
08NL070
08NL069
Blackwall Peak
Manning Park
Mount Kobau
12442500
12442000
12442300
Harts Pass
Salmon Meadows
SIMILKAMEEN RIVER
SIMILKAMEEN SUB-BASIN
OKANAGAN BASIN
WATERBODY
ZOSEL DAM
SNOW SURVEY
HYDROMETRIC STATION
SCALE - 1:500,000
0 3 6 9 12 15 Km
N
Coordinate System: NAD 1983 UTM ZONE 11N
Units: METERS
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SIMILKAMEEN HYDROLOGIC MODEL
HYDROMETRIC AND SNOW SURVEY LOCATIONS
FIGURE 2.1

Table 2.2 Snow survey locations used in model calibration.

Station ID	Station Name	Measurement Type	Elevation (m)	Operating Period
2G03P	Blackwall Peak	Automatic	1940	2003-2015
515	Harts Pass	Automatic	1978	1983-2020
728	Salmon Meadows	Automatic	1359	1982-2020
2G01	Copper Mountain	Manual	1310	1949-1971
2G06	Hamilton Hill	Manual	1490	1960-2020
2G04	Lost Horse Mountain	Manual	1920	1960-2020
2G05	Missezula Mountain	Manual	1550	1960-2020
2F12	Mount Kobau	Manual	1810	1966-2020
2G02	Nickel Plate	Manual	1890	1949-1986
2G01A	Sunday Summit	Manual	1310	1959-1996
2F01	Trout Creek	Manual	1430	1935-2014

2.2.1 Water demand

Associated Environmental, Inc. provided sub-basin scale water demand data for the Similkameen Basin, both for the historical period, and for the ensemble climate projection. A description of the water demand methodology is available in Appendix A.

2.2.2 Spatial data

Land cover, topographic, and soil data were used as a basis for model discretization and parameterization. Table 2.3 summarizes the spatial data sources used in the model development.

The majority of the Similkameen Basin is forest covered, and thus slight variations in forest cover (e.g. through forest harvesting, variations in tree type, etc.) play a more significant role in the landcover than in the Okanagan, which contains more grasslands, farmlands, urban areas, and open water. We employed the more detailed NALCMS landcover dataset to better capture these higher resolution changes in the forest canopy, rather than the coarser "Globcover" 2009 dataset used in the Okanagan model[3].

Additionally, the Similkameen Basin contains more area within the United States, and thus more attention to international soil layer variation was required (using the gNATSGO dataset); for the

[3] http://due.esrin.esa.int/page_globcover.php

Okanagan model, soil coverage within the United States was simply extended south from the adjacent Canadian polygon.

Table 2.3 Spatial data used in model development.

Data Type	Description	Coverage	Source
Land Cover	30 m land cover information derived from 2015 Landsat imagery	Entire basin	North American Land Change Monitoring System (NALCMS)[4]
Soil	Soil data based on Soils of the Okanagan and Similkameen Valley (Wittneben, 1986)	Canada	BC Ministry of Environment and Climate Change Strategy (BCMoECC)[5]
Soil	Composite database for the US based on best available soils information (determined by creators)	US	Gridded National Soil Survey Geographic Database (gNATSGO)[6]
Digital Elevation Map (DEM)	1 arc-second resolution data	Entire basin	National Elevation Dataset (NED)[7]
Hydrography	1:20,000 hydrography delineated lakes, watercourses, and drainage basins	Canada	BC Fresh Water Atlas[8]
Hydrography	1:24,000 or greater hydrography delineated lakes, watercourses, and drainage basins	US	National Hydrography Dataset (NHD)[9]

2.3 Model development

The hydrologic model of the Similkameen Basin was developed using the Raven hydrologic modelling framework (Craig et al., 2020). Raven is an open-source, flexible, hydrologic modelling framework which allows for multiple numerical schemes, model structures, discretization schemes and interpolation approaches to be used in the development of a hydrologic model. Raven uses a large library of hydrologic process algorithms and forcing generators to develop model structures which can be easily changed to better represent the physical system.

[4] http://www.cec.org/north-american-environmental-atlas/land-cover-30m-2015-landsat-and-rapideye/

[5] https://catalogue.data.gov.bc.ca/dataset/soil-survey-spatial-view

[6] https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcseprd1464625

[7] https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/?&cid=nrcs143_021626

[8] https://www2.gov.bc.ca/gov/content/data/geographic-data-services/topographic-data/freshwater

[9] https://www.usgs.gov/core-science-systems/ngp/national-hydrography/national-hydrography-dataset

2.3.1 Spatial configuration

The Similkameen model is based on a semi-distributed discretization scheme which breaks the entire basin into smaller subbasins. Within these subbasins the landscape is further discretized into hydrologic response units (HRUs) which represent non-contiguous land parcels that have a similar hydrologic response.

Subbasins dictate the locations that streamflow can be extracted from a Raven model, and as such are a determined based on a combination of both hydrologic appropriateness and the needs of the end user. Subbasins were delineated from the DEM based on hydrometric gauge and reservoir locations, major river confluences, and consultation with the IJC, resulting in 34 subbasins.

HRUs were discretized based on 200 m elevation bands and 6 land cover types. Land cover types were simplified from the original classification structure, shown in Table 2.4. Each HRU was characterized with the required attributes:

- Centroid latitude and longitude
- Mean elevation
- Dominant aspect
- Mean slope
- Dominant land cover from the NALCMS 2015 30 m land cover classification[10]
- Dominant soil drainage from the BCMOECC and gNATSGO data sources. Soil drainage was simplified as per Table 2.5.

[10] http://www.cec.org/north-american-environmental-atlas/land-cover-30m-2015-landsat-and-rapideye/

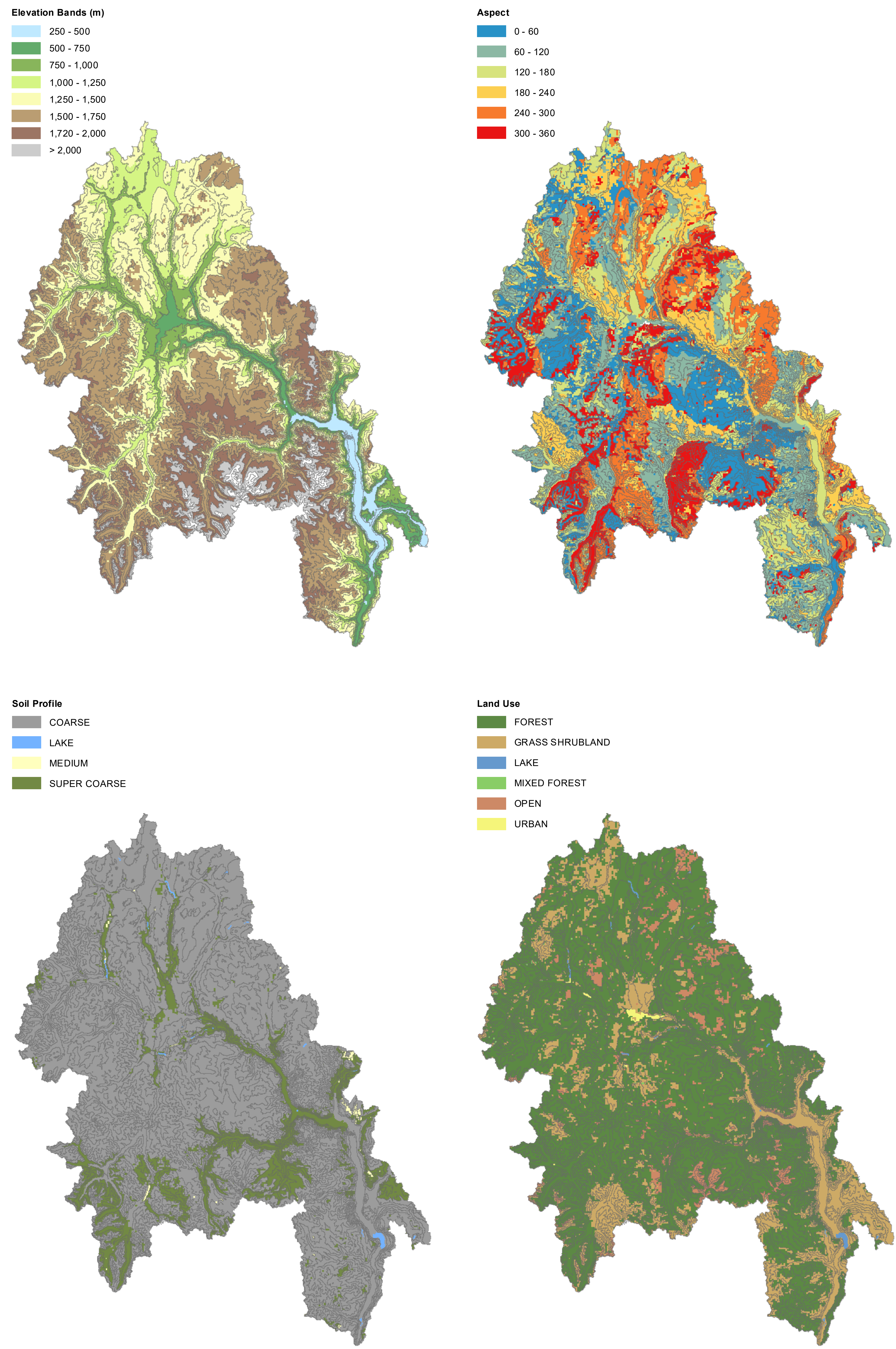
Table 2.4 Land cover simplification from NALCMS 2015.

NALCMS 2015 Land Classification	Simplified Raven Classification
Temperate or sub-polar needleleaf forest	Forest
Sub-polar taiga needleleaf forest	Forest
Temperate or sub-polar broadleaf deciduous forest	Mixed Forest
Mixed Forest	Mixed Forest
Temperate or sub-polar shrubland	Grass Shrubland
Temperate or sub-polar grassland	Grass Shrubland
Sub-polar or polar grassland-lichen-moss	Grass Shrubland
Wetland	Grass Shrubland
Cropland	Grass Shrubland
Barren Lands	Open
Urban and Built-up	Urban
Water	Lake

Table 2.5 Simplification of soil classification.

Source	Original Classification	Simplified Raven Classification
BCMoECC	Moderately Well Drained (MW)	Medium
	Poorly Drained (P)	Medium
	Rapidly Drained (R)	Super coarse
	Well Drained (W)	Coarse
gNATSGO	Somewhat excessively drained	Super coarse
	Well drained	Coarse
	Moderately well drained	Medium
	Poorly drained	Medium
	Somewhat poorly drained	Medium

The initial discretization of HRUs led to many small HRUs (referred to as sliver HRUs), which increase computation time while providing little benefit to the results. HRUs were first simplified within GIS by merging slivers that were less than 0.05 km^2 with larger, neighbouring HRUs. HRUs were further simplified by consolidating HRUs which were less than 0.5% of the subbasin area with similar HRUs (defined based on land cover, slope, aspect and elevation) using the RavenR package (Chlumsky, 2020) for the statistical programming language 'R' (Hornik, 2016), resulting in 913 HRUs. Major subbasins are shown in Figure 2.1 while a summary of HRU information is provided in Figure 2.2.



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: 3005472 DATE:10-FEB-2021

SIMILKAMEEN HYDROLOGIC MODEL

HRUs

FIGURE 2.2

2.3.2 Model structure

Model structure refers to the hydrologic processes simulated within the model (e.g. snowmelt, subsurface flow, etc.) and the methods used for these processes. As Raven allows for inclusion or exclusion of any desired hydrologic process and contains a library of hundreds of different process methods, determination of the appropriate model structure requires familiarity with the hydrology of the region, and experience with the most appropriate structure for that region.

For the Similkameen Basin, NHC used nearly the same model structure as the Okanagan Raven model (NHC, 2020). The model structure was based on the HBV-EC hydrologic model structure (Hamilton et al., 2002) with the configuration and routines changed as necessary to better represent local conditions during model configuration.

Primary changes to the base HBV-EC model structure included:

- Changing the evapotranspiration routine from the default monthly average values of HBV-EC to the daily empirical method of Hargreaves and Samani (1985).
- Modification of the handling of lake evapotranspiration from a constant from the second soil reservoir to open water evaporation between lake storage and the atmosphere.
- Addition of level pool reservoir routing for basin reservoirs and linear lake storage and release for surface water.
- Inclusion of water demand on a subbasin scale. This is described in Appendix A.

Water is routed between subbasins using Raven's plug flow routing algorithm. Channel geometry for the mainstem of the Similkameen River was based on survey data collected in prior work done by NHC for FortisBC. For tributaries to the mainstem, channel geometry was estimated as a trapezoidal channel using bankfull widths and depths estimated by subbasin area and mean annual peak flow, as outlined in the methodology by Andreadis et al. (2013).

As opposed to the Okanagan Basin, water storage (either through reservoirs or natural lakes which function as fixed reservoirs) plays a relatively small role on the Similkameen River. Thus, simplified storage was modelled either as a weir equation only (Palmer Lake and Missezula Lake) or as a combination of the relationship between stage-volume and weir equation when stage-volume data was available[11] (Issitz Lake, Otter Lake, and Wolfe Lake). For natural lakes, crest heights and weir coefficients were determined through manual testing and comparison with level observations.

The model uses a daily timestep to simulate available climate data from 1950 to 2010. Calibration and validation periods are further discussed in Section 3.

[11] https://a100.gov.bc.ca/pub/acat/public/welcome.do

3 CALIBRATION

Calibration of the Similkameen model was performed as an iterative process using a mixture of manual methods and automated calibration with Ostrich (Matott, 2017) and followed a similar procedure as NHC's Okanagan Raven model. First, parameters from the Okanagan model were transferred to the Similkameen raven model, and the overall realism of the model was evaluated. Second, calibration moved into automated methods with Ostrich, and sought to maximize hydrograph performance on gauged watersheds. Finally, the internal realism of the resulting calibration parameter sets were evaluated through assessing snow results and the hydrograph volume results.

3.1 Regime Curve

The broad realism of the hydrologic model was first investigated (and rechecked through the calibration process) by regime curve visualization. Starting with the water balance allowed us to determine if the broad hydrologic processes for the HBV-EC emulation were appropriate for the Similkameen Basin. The monthly basin-wide water balance (regime curve) is shown in Figure 3.1, and indicates a mean annual evapotranspiration of 500 mm/year, peaking in the early summer. As expected for a water stressed basin, the actual evapotranspiration (AET) peaks before potential evapotranspiration (PET). AET is greater than PET from November through May. This is a result of sublimation of precipitation from the forest canopy being included in the AET and not included in the calculated PET values.

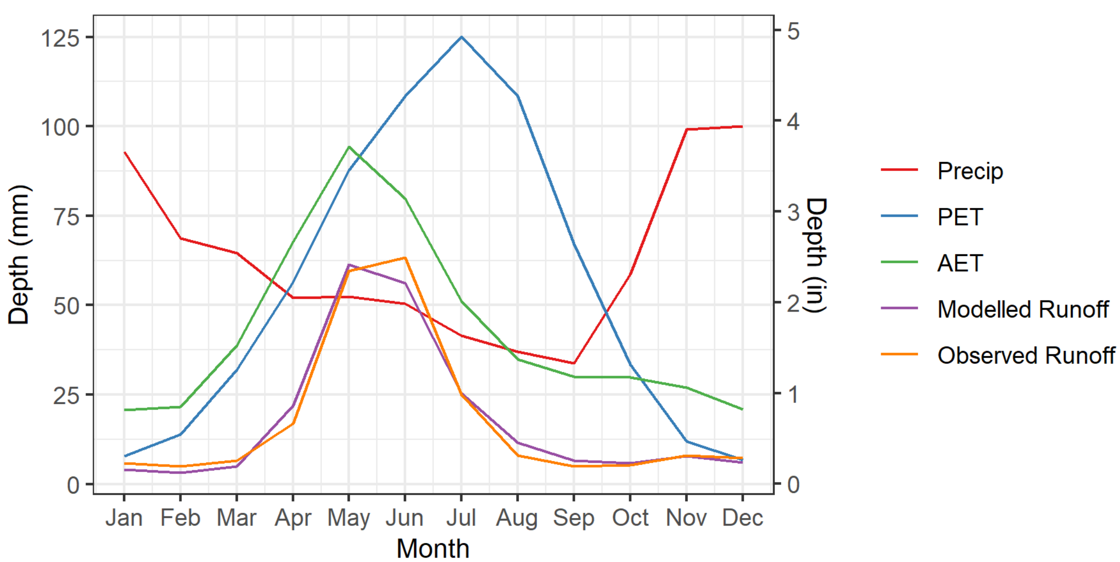


Figure 3.1 Regime curve showing monthly basin-wide water balance.

3.2 Ostrich

A split-sample calibration approach was used where January 1975 through December 1984 and January 1995 to December 2004 were used for calibration and January 1985 to December 1994 and January 2005 December 2009 were used for validation. This approach helps eliminate possible bias in the forcing data and helps to reduce the impact of long-term climatic variability on the model results. For example, the PDO is a pattern of pacific climate variability that can last decades and is defined by warm and cool phases. By splitting the calibration period into two different decades, cool periods in the 1970s and 2000s were captured along with warm periods in the 1980s and 1990s[12]. The full distribution of calibration and validation periods is shown in Figure 3.2.

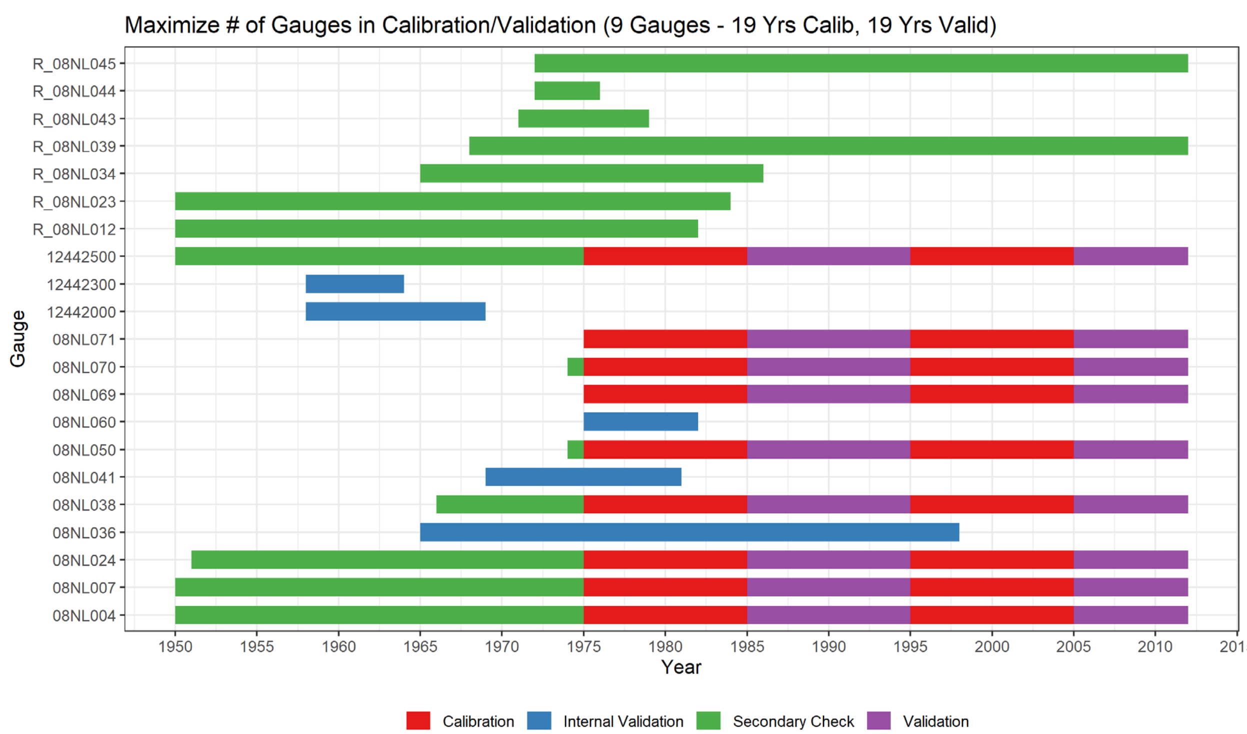


Figure 3.2 Calibration/Validation partitioning for the Similkameen Basin.

Due to the similarity of the Similkameen Basin to the Okanagan Basin, the Okanagan model structure and parameter set were used as the initial parameter set for the Similkameen Basin. Automatic calibration was performed using Ostrich (Matott, 2017), a model independent calibration tool. A total of 57 soil, land use, and vegetation parameters were manipulated during automatic calibration. The soil parameters control the partitioning and movement of water between the atmosphere, soil storage, and surface water. Land use and vegetation parameters primarily control the accumulation and melt of snow and the interception of precipitation. The parameter range was constrained during multiple iterations of

[12] https://www.ncdc.noaa.gov/teleconnections/pdo/

automatic calibration to ensure the model provided realistic simulation of other processes beyond streamflow.

As model requirements meant that both high and low flow performance was desired from the Similkameen model, a multi-objective approach was used to maximize the overall model performance and the low flows at the Similkameen Nighthawk gauge. To do so, the pareto archived dynamically dimensioned search (PADDS) multi-objective algorithm (Asadzadeh and Tolson, 2009) was used within Ostrich to find non-dominated solutions. Non-dominated solutions refer to solutions that can only improve one objective by degrading another objective.

Within Ostrich, 3 objectives were defined. The first objective was defined as a weighted average of the nine calibration gauge's Nash Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970). NSE is a commonly used performance metric that ranges from -∞ to 1, with 1 indicating the observations and simulations are the same. A larger weight was placed on the Similkameen River near Nighthawk gauge. Objective 2 was the log NSE of the Similkameen Nighthawk gauge. Using the log NSE places a greater weight on low flows. The third objective was to minimize the percent bias of the Similkameen Nighthawk gauge. To account for minimizing negative biases, the squared percent bias was used for the objective.

Figure 3.3 shows the three parameter pareto front of the non-dominated solutions and the selected solution set (starred). This solution set was chosen as it provides a reasonable trade-off between low flow and overall model performance.

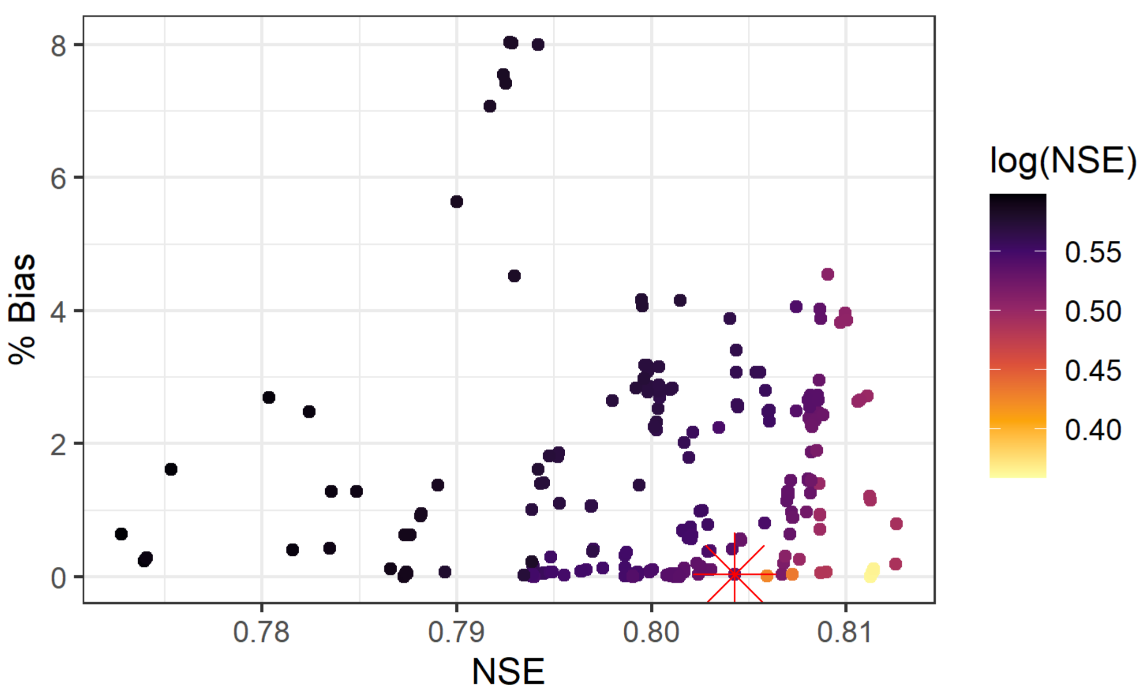


Figure 3.3 Pareto front showing non-dominated solution set. The red starred solution was chosen as the solution for climate projection.

3.3 Calibration Results

3.3.1 Streamflow

The calibrated model performed generally well at all scales of the model, from the smaller headwater subbasins to the outlet. The model was generally successful in simulating flows at the outlet (Similkameen River near Nighthawk) with NSE value of 0.87 and 0% percent bias. For the Similkameen Nighthawk gauge, validation displayed a slight drop when compared to calibration performance. Maintaining model performance outside the calibration period is a useful test of whether a model is overfit to the calibration period and helps to increase our confidence in the results of climate projection modelling with this model. Performance metrics for the nine gauges used during the calibration and validation periods are summarized in Table 3.1.

Table 3.1 Performance metrics during calibration and validation at gauges used in calibration

Gauge ID	Gauge Name	Calibration			Validation		
		NSE	Log-NSE	% Bias	NSE	Log-NSE	% Bias
12442500 08NL002	Similkameen River near Nighthawk	0.87	0.53	0%	0.83	0.71	-1%
08NL071	Tulameen River below Vuich Creek	0.61	0.34	-24%	0.64	0.54	-24%
08NL070	Similkameen River above Goodfellow Creek	0.75	0.43	-27%	0.77	0.41	-27%
08NL069	Pasayten River above Calcite Creek	0.80	0.57	13%	0.80	0.63	15%
08NL050	Hedley Creek near the mouth	0.62	0.61	-30%	0.50	0.65	-30%
08NL038	Similkameen River near Hedley	0.86	0.42	1%	0.84	0.74	-1%
08NL024	Tulameen River at Princeton	0.78	0.47	0%	0.79	0.68	-5%
08NL007	Similkameen River at Princeton	0.84	0.56	-9%	0.85	0.58	-5%
08NL004	Ashnola River near Keremeos	0.82	0.40	9%	0.77	0.64	13%

Some of the smaller subbasins (Tulameen River below Vuich Creek, Similkameen River above Goodfellow Creek, Pasayten River above Calcite Creek, Hedley Creek near the Mouth) show a larger percent bias than the mainstem. Different penalty configurations for percent bias which applied greater weight to these gauges were attempted in Ostrich; however, the results showed a decrease in performance at the outlet. Given the objectives of this work, we continued with the method showing best performance at the model outlet.

Figure 3.4 through Figure 3.6 show example hydrographs at select gauges within the basin. The consistent underestimation in volume is obvious at Hedley Creek near the mouth (Figure 3.5).

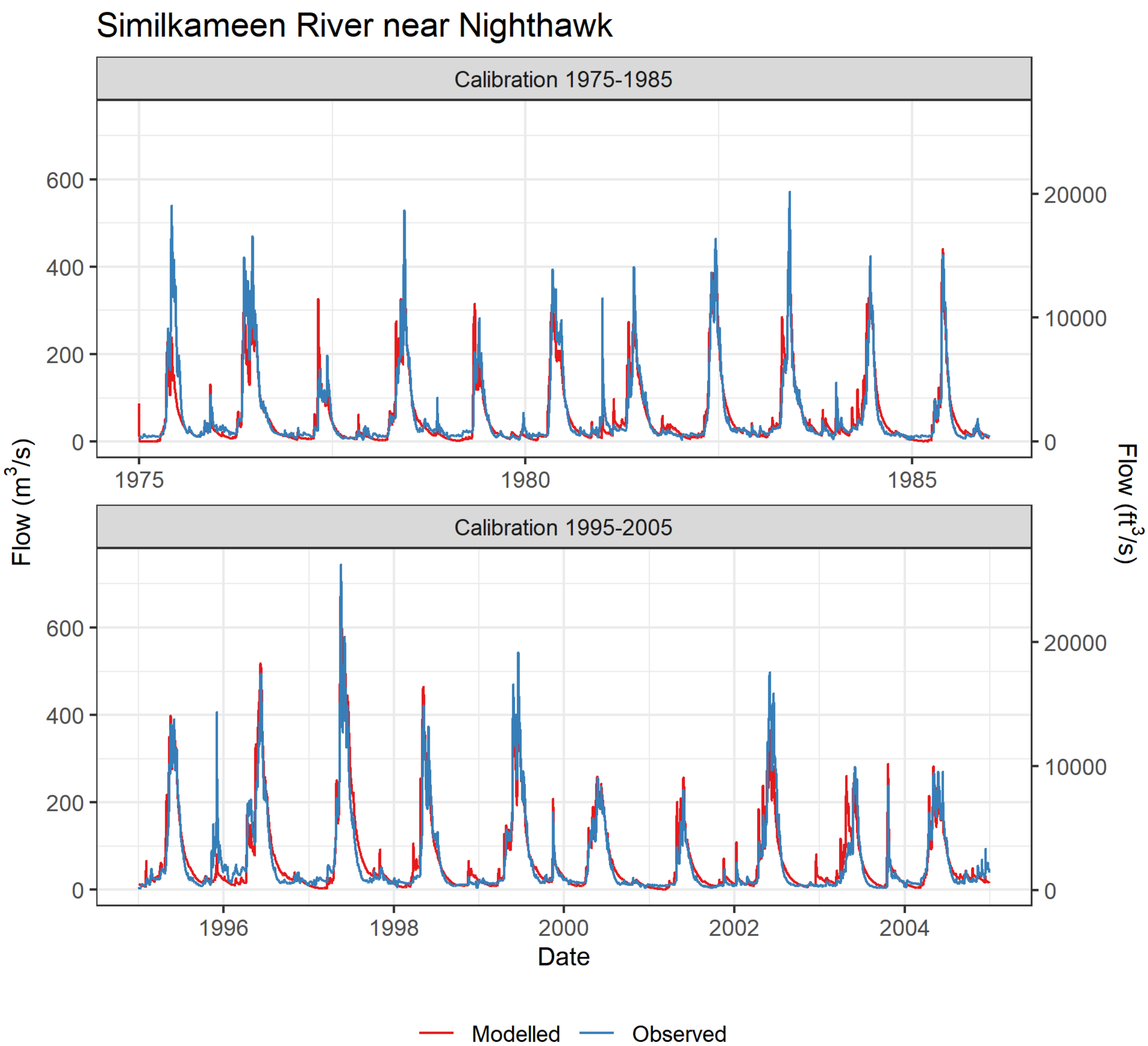


Figure 3.4 Modelled and observed hydrographs at Similkameen River near Nighthawk.

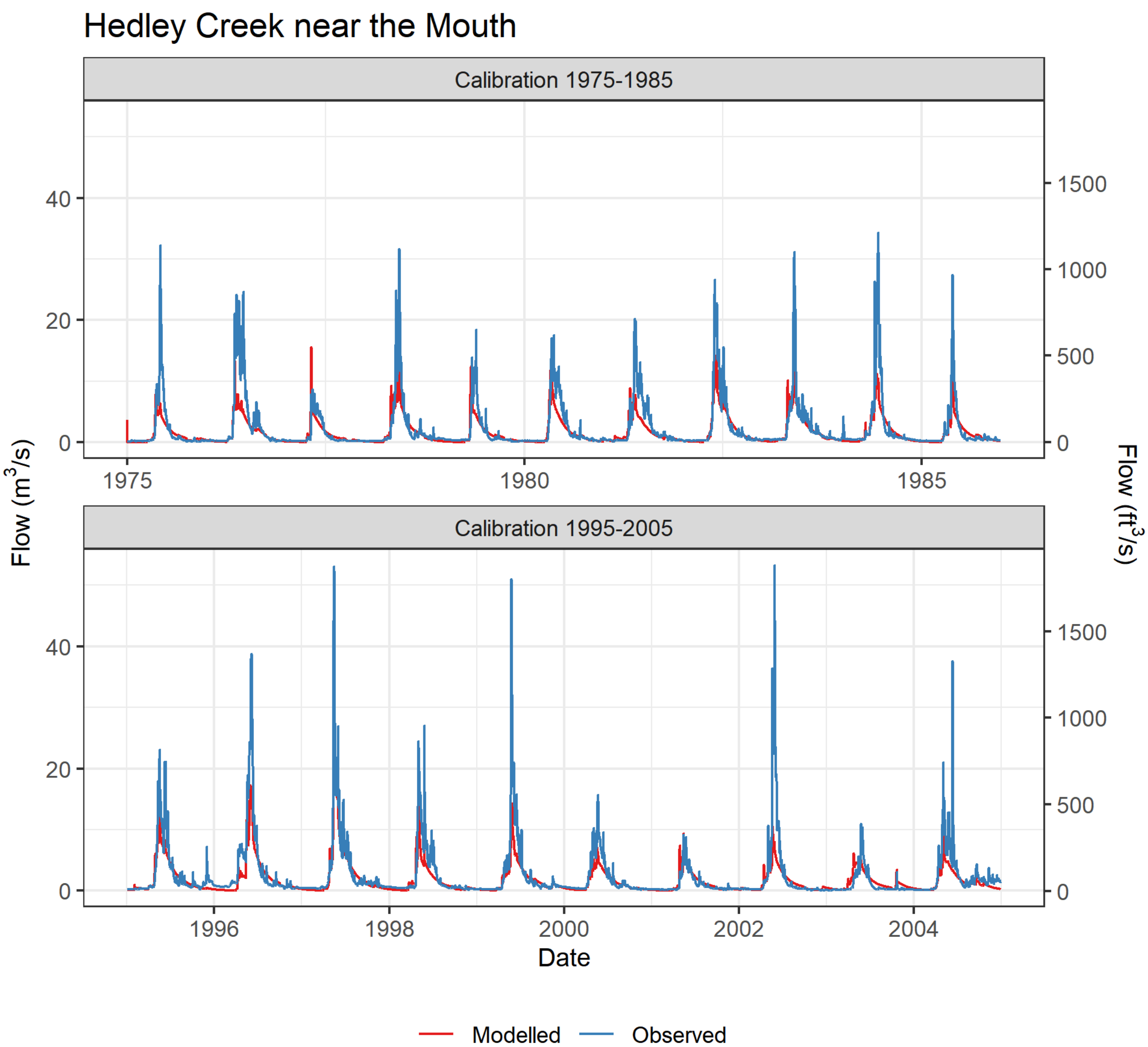


Figure 3.5 Modelled and observed hydrographs at Hedley Creek near the Mouth.

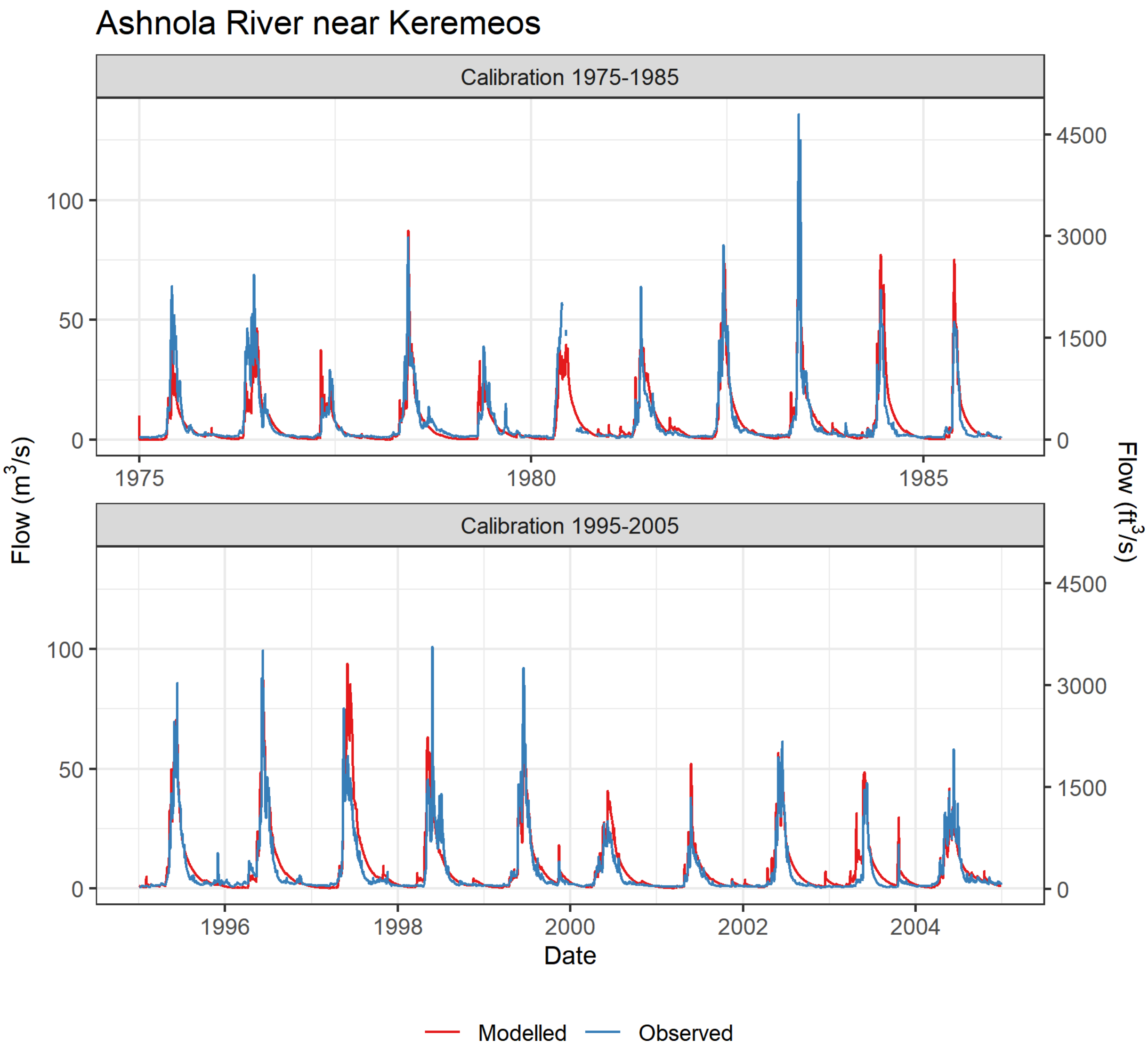


Figure 3.6 Modelled and observed hydrographs at Ashnola River near Keremeos.

3.3.2 Snow

Snow modelling provides important information about both the snow processes within the model and (perhaps even more importantly) about the accuracy of high elevation meteorological inputs to the hydrologic model. Stahl et al (2006) note that uncertainty about vertical temperature gradients, and a general lack of high elevation weather observations is often a critical source of hydrologic uncertainty in British Columbia.

While it is possible to directly calibrate snow parameters to maximize reproduction of observations at snow pillows, our experience is that this can lead to model over calibration. The small scale variations in wind loading, canopy interception, and measurement can lead to variations at point snow observation sites that are not directly representative of the high elevation snowpack at a basin scale. Thus, we use snow as an important method for 'internal validation' of a hydrologic model, but do not calibrate to it directly.

Snow accumulation and melt within the model was compared with manual and automatic snow survey data, as shown in Figure 3.7 and Figure 3.8. The model appears to have site specific biases in simulated SWE at some snow survey sites. The percent bias at the automatic sites is summarized in Table 3.2.

Table 3.2 Model bias at automatic snow survey sites

Site ID	Site Name	% Bias
2G03P	Blackwall Peak	-39
515	Harts Pass	-30
728	Salmon Meadows	9

Some manual stations also show variable bias. For example, SWE is underestimated at Lost Horse Mountain and Mount Kobau but overestimated at Hamilton Hill and Trout Creek. Snow measurements are a point measurement in space and, in the case of manual measurements, time. They are influenced by site specific characteristics like drifting and canopy interception which can have major influences on snow accumulation on a site-by-site basis. The snow survey data is compared to simulated data for the HRU in which the survey site falls, which have a median elevation, aspect, and generalized land cover based on the HRU's entire non-contiguous area. As noted above, the model is not calibrated to exactly match the snow survey data as this would likely result in over parameterization but is used to generally capture the snow accumulation and melt. If the model had consistent over- or underestimation at all sites this might indicate errors within the precipitation data (orographic correction), temperature data, or model parameters. So, despite the site-specific biases NHC considers these results reasonably strong for the Similkameen as a whole.

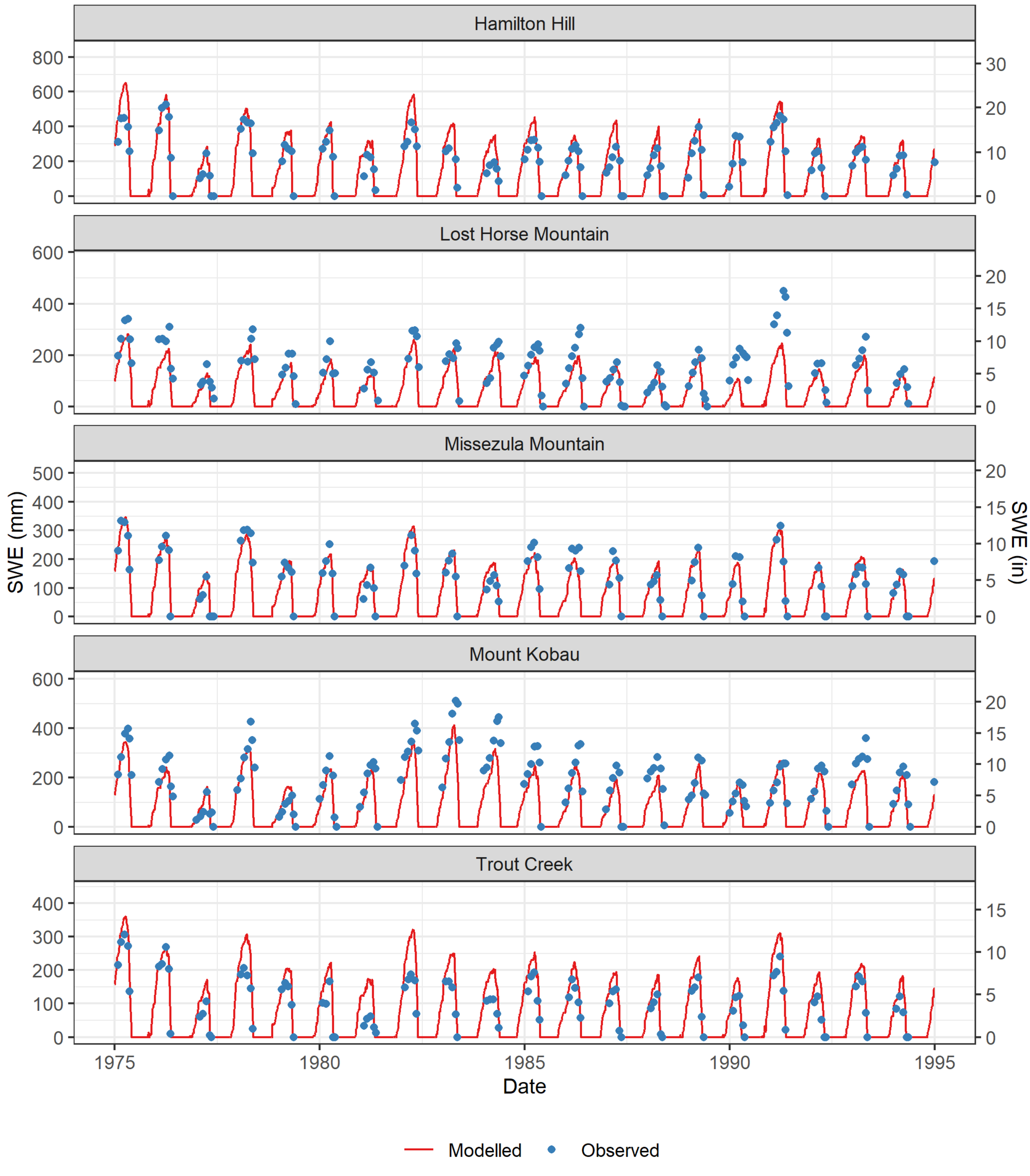


Figure 3.7 Select manual snow survey sites showing modelled and observed snow water equivalent (SWE).

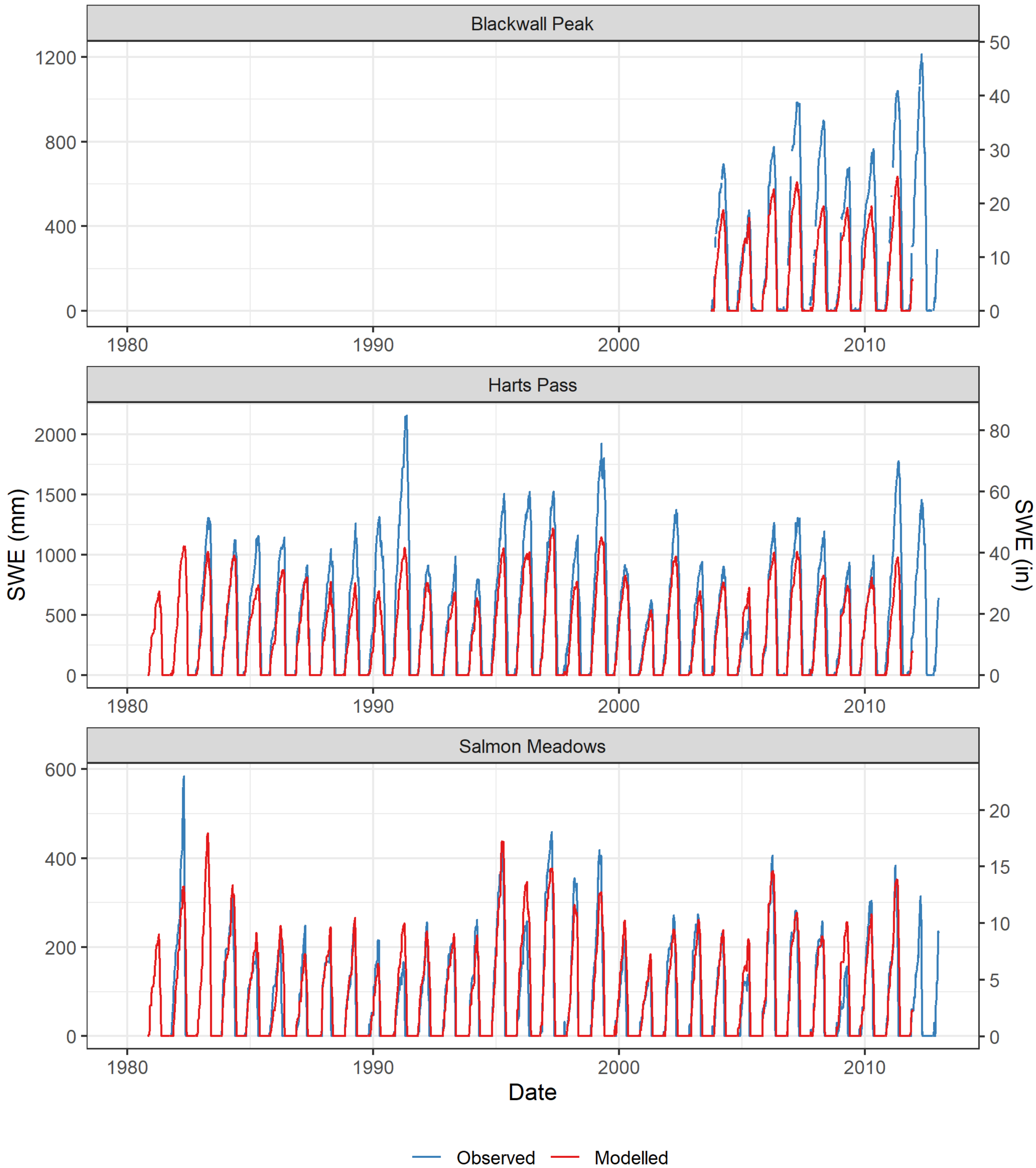


Figure 3.8 Select automatic snow survey sites showing modelled and observed SWE.

3.3.3 Freshet Volumes

Though optimization focused on hydrograph results, the ability of the model to reproduce the April-July freshet volumes at the Nighthawk gauge during calibration and validation periods was also investigated. Calibration and validation refers to the periods mentioned in the prior section; however, both periods (Figure 3.9) could be interpreted as validation, as the model was not directly optimized to maximize seasonal volume performance for either period. The overall bias during both calibration and validation was 3.3% with an overall root mean square error of 217,885 acre-feet. During calibration, all drought criteria years were correctly identified. In validation 3 years were misclassified due to over-prediction of freshet volume.

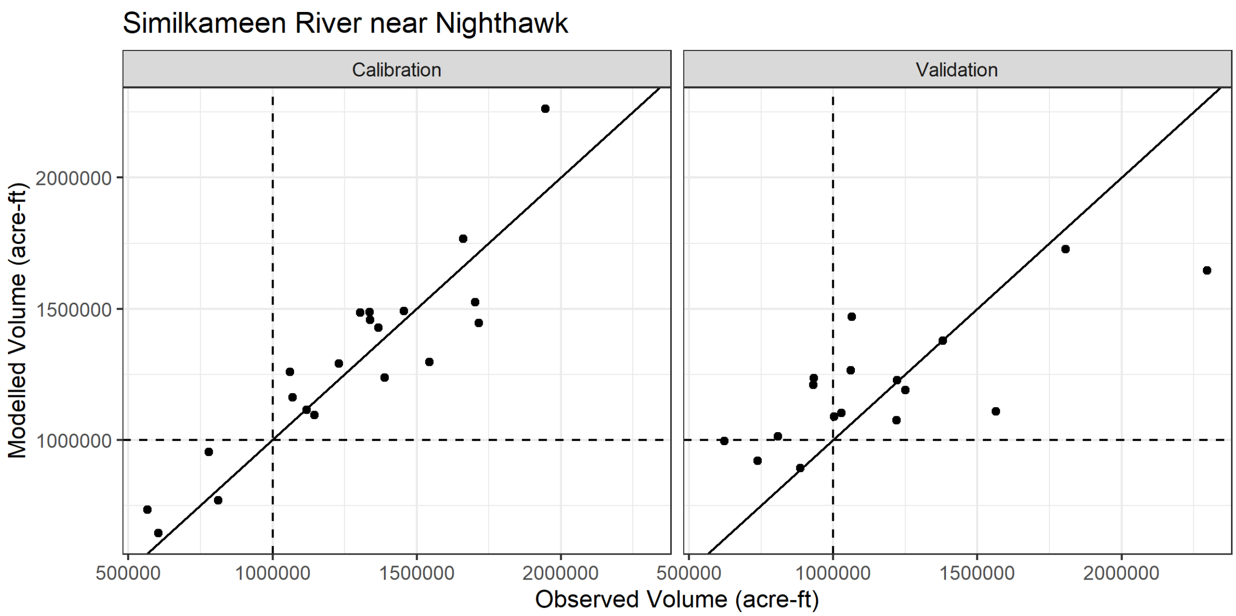


Figure 3.9 Modelled and observed April to July volumes at Similkameen near Nighthawk. The dashed line at 1,000,000 acre-feet represents the volume when drought operations are enacted.

4 ENSEMBLE PROJECTIONS

4.1 Ensemble forcing data

The calibrated Raven model was run from 1950-2100 using the 50 member Canadian Large Ensembles Dataset, Version 1 (CanLEADV1) dataset, which is a regional dynamically downscaled (to 0.5° spatial resolution) output from the Canadian Earth System Model (CanESM2) climate model for the future representative concentration pathway (RCP) 8.5. The RCP is a greenhouse gas concentration trajectory, with the '8.5' representing this RCP's net increase of 8.5 W/m^2 (watts per metre squared) in global average radiative forcings at the end of this century (2100).

The CanLEADV1 ensemble dataset was downscaled to statistically match the observation dataset during the overlapping calibration period (i.e. 1950 to 2012) for the entire Okanagan Similkameen area by NHC (2020) using the 'ClimDown' package[13] developed by the Pacific Climate Impacts Consortium (PCIC) for R. For the Similkameen Basin, the downscaled ensemble dataset was aggregated to an irregular grid, with one point corresponding to one HRU, in an identical manner as the gridded observations dataset.

Full analysis of the dataset and description of the downscaling is available in NHC (2020). In this analysis of the CanLEADV1 dataset, NHC found that these climate projections ranked as both a warmer and wetter projection scenario than average. However, the dataset was not an outlier when compared to other climate model results for either temperature or precipitation.

Changes in water demand were forecasted, using four ensemble members (two average members and the warmest and coldest 2070-2100 growing periods), by Associated Engineering, Inc. Full discussion of water demand forecasting methods is available in Appendix A. To uniformly distributed the four demand ensemble members, NHC randomized assignment of the four demand projections to each of the 50 ensemble meteorologic datasets.

4.2 Predicted hydrologic change

This section covers broad scale results of the potential impacts of climate change on the Similkameen River. In general, results are separated by 30-year climatological periods, as in NHC (2020). In analysis of the CanLEADV1 dataset, NHC (2020) found that the expected increase in minimum daily temperature is greater than 5°C by the year 2100 across the entire Okanagan-Similkameen region. The maximum daily temperature is projected to rise by 3°C to 4°C. This temperature increase is enough to produce large changes in the hydrology of the Similkameen Basin. Particularly, rises in the minimum daily temperature carry important consequences as they diminish the capacity of the snowpack to lose during the night the solar heat gained during the day, thus raising snowpack temperature and promoting snowmelt. These temperature changes, in conjunction with projected changes in precipitation in the CanLEADV1 dataset, lead to notable expected changes to the hydrology of the Similkameen Basin.

4.2.1 Precipitation and snowpack

The future monthly distribution of precipitation is shown in Figure 4.1**.** This figure illustrates that total precipitation is expected to increase in all months except July to September, when it is expected to remain approximately the same. Though total precipitation increases in fall, winter, and spring, Figure 4.2 shows that increases in winter temperatures result in overall decreasing winter snowfall accumulation (and an implied shift to more winter rainfall), with the most severe reductions occurring at the middle elevations of the watershed. This figure illustrates that in many cases, the seasonal snowpack is expected to disappear more than one month earlier by the end of the century than at the present time.

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[13] https://cran.r-project.org/web/packages/ClimDown/index.html

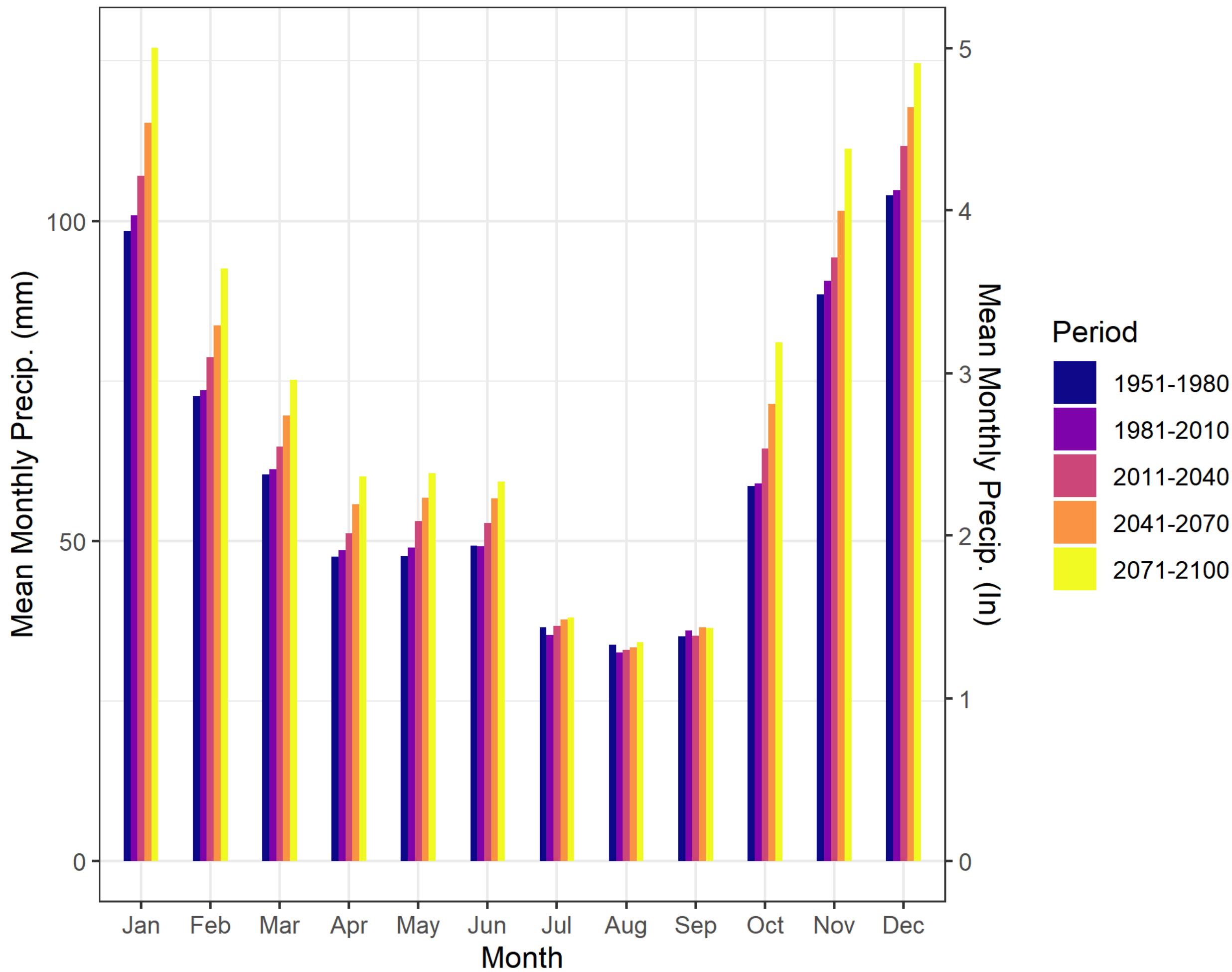

Figure 4.1 Changes in basin-wide mean monthly precipitation, separated by month and climatological period.

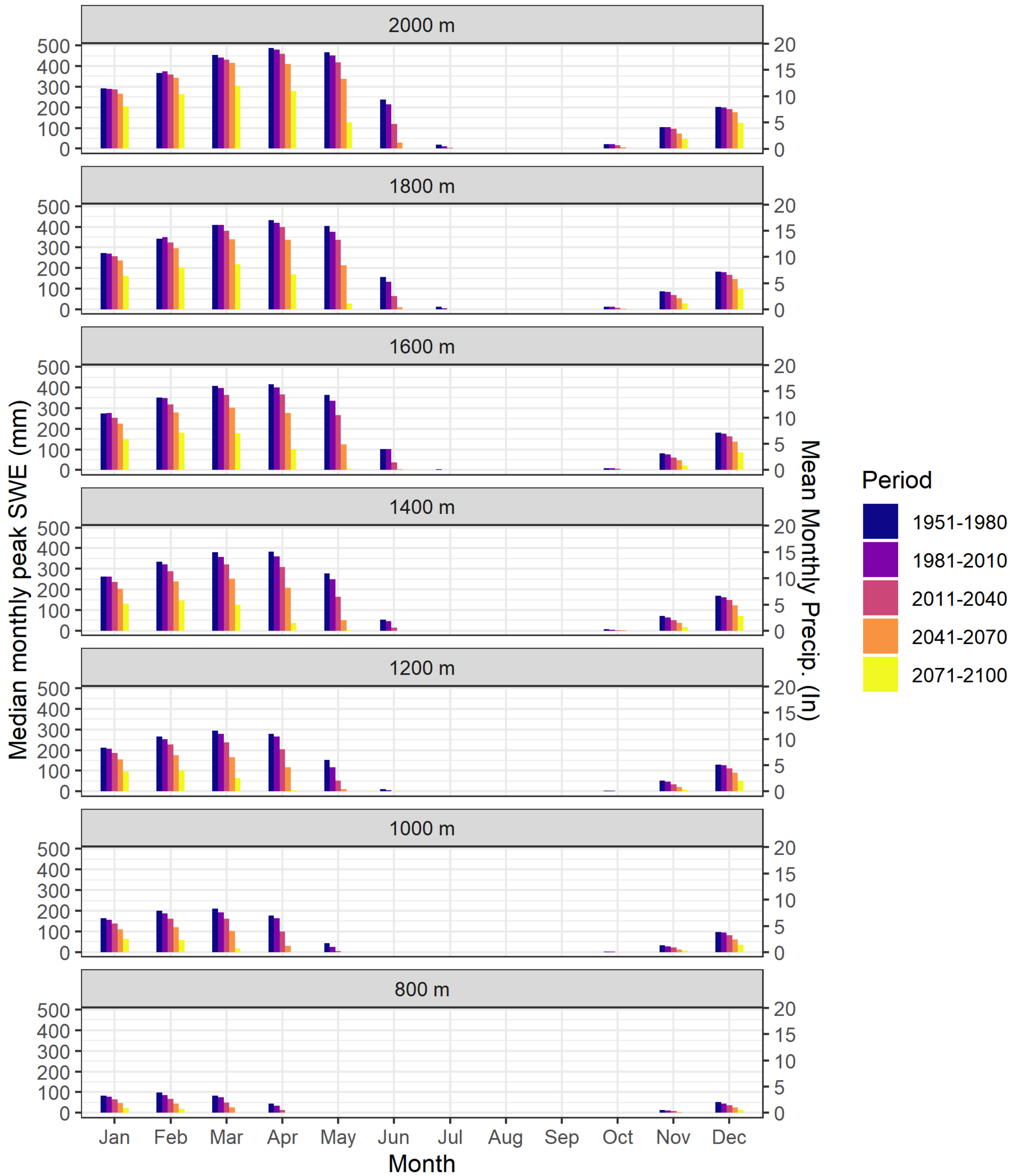

Figure 4.2 Ensemble median peak monthly snow water equivalent (SWE), separated by climatological period and basin elevation band.

4.2.2 Annual yield and hydrologic regime

The shift from winter snowfall to more winter rainfall results in substantial changes to the overall hydrologic regime of the Similkameen River. Figure 4.3 summarizes the shift in regime of the basin, both for the median flows (red line), and for the distribution of flows throughout the year. The figure illustrates that the Similkameen River shifts towards a mixed regime by the middle of this century. The spring freshet is no longer the dominant hydrologic event of the year, as winter flows begin to increase, and the spring freshet becomes smaller. Additionally, while fall peak flows can occur at the present time on the Similkameen River, peak flows (i.e. the light grey bands) become much more common in fall by the middle and end of the century.

Though the model projects depletion of the spring freshet, the annual water yield (including net impacts of water demand) increases slightly by the end of the century (Figure 4.4), indicating that increases in annual precipitation appear to compensate for increases in evapotranspiration (due to warmer temperatures) and increases in water demand.

Based on the evidence of approximately normal distributions of annual water yield by climate period (Figure 4.4), we performed pairwise t-tests in the statistical software 'R' to assess whether the changes in annual water yield are statistically significant (at a 0.05 level). Pairwise t-tests are a series of two-tailed t-tests which test the null hypotheses (that there is no difference between groups) between all different pairs of groups in the dataset[14]. This paired testing results in a matrix of t-values and p-values. The group of p-values are then adjusted for groupwise error rates using the Bonferroni correction (Bonferroni, 1936).

Paired t-test results are shown in Table 4.1**,** and illustrate that the annual water yield displays no significant change between 1951-1980 and 1981-2010, but beyond the present, all future periods are significantly different than the prior. However, the changes in annual yield are more subtle than the expected redistribution of the hydrograph, and further analysis (e.g. with different climate forcings) would be prudent before making conclusions on projected changes in water yield.

[14] https://stat.ethz.ch/R-manual/R-devel/library/stats/html/pairwise.t.test.html

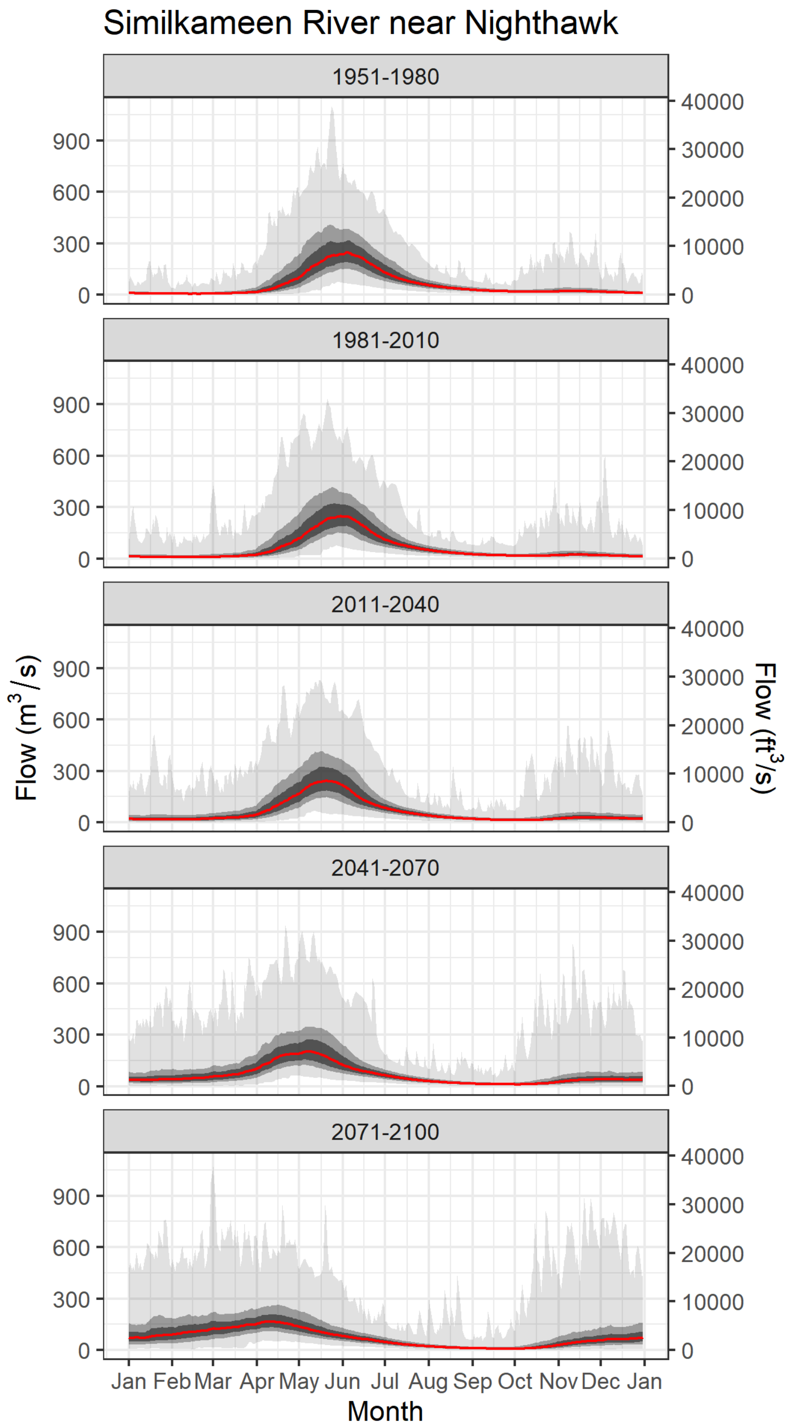

Figure 4.3 Projected changes in hydrologic regime for the Similkameen River near Nighthawk, WA. Red line represents median flow for the period, grey bands represent 25th-75th percentile, 10th-90th percentile, and maximum/minimum, respectively according to shade.

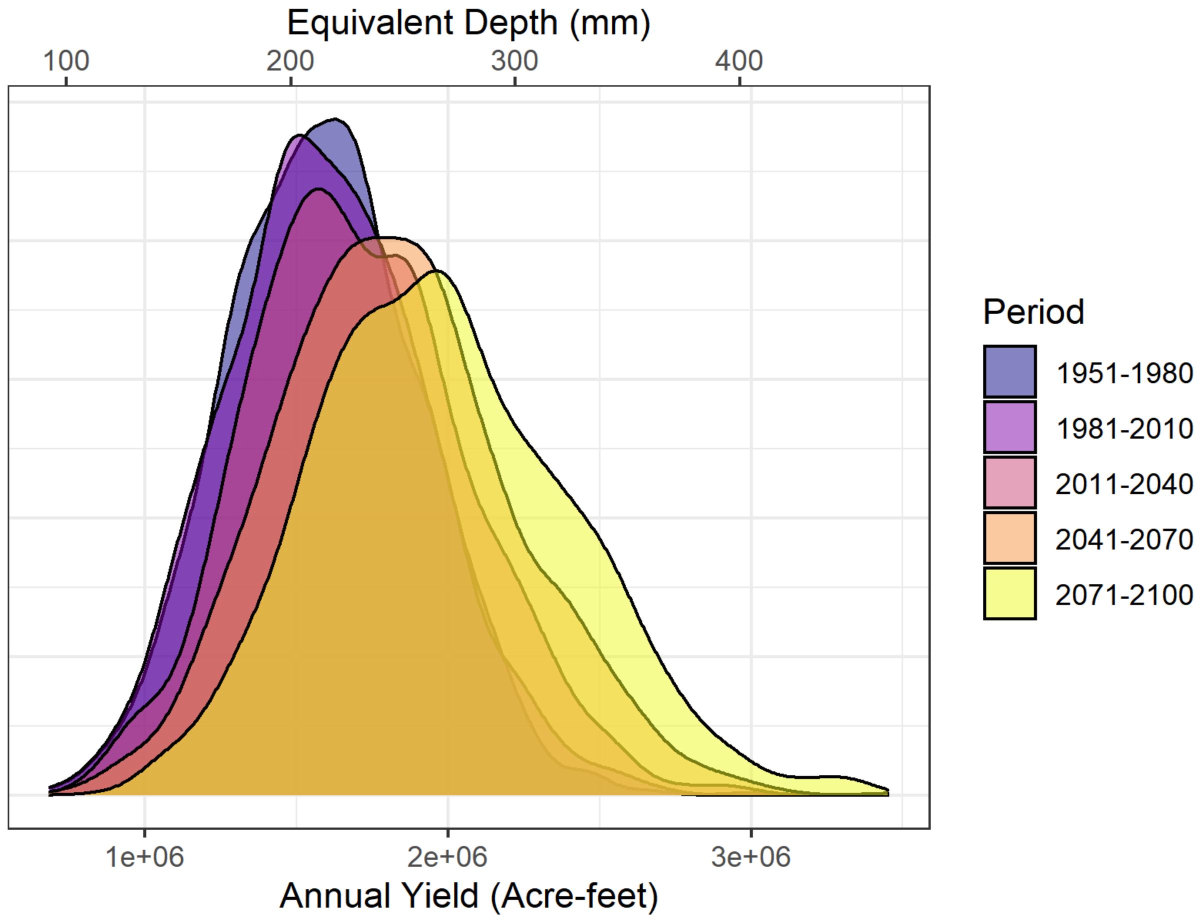

Figure 4.4 **Probability density plot of annual water yield (with net impacts of water demand included) for the Similkameen River near Nighthawk, WA, separated by 30-year climatological period.**

Table 4.1 **Pairwise t-test results for comparing distributions of annual water yield by climatological period. E = 10^x. Bold numbers indicate p-values for comparison with the prior climatological period.**

	1951-1980	1981-2010	2011-2040	2041-2070
1981-2010	**1**	N/A	N/A	N/A
2011-2040	<1E-10	**<1E-10**	N/A	NA
2041-2070	<1E-10	<1E-10	**<1E-10**	N/A
2071-2100	<1E-10	<1E-10	<1E-10	**<1E-10**

4.2.3 Extreme Flows

Though not directly within the scope of this work, we briefly investigated potential changes in extreme flows for the Similkameen River from the present through the end of the century. By their definition, at the tails of flow distributions, extreme flows are the most difficult to model and to predict potential changes. However, extreme flows are some of the most significant situations for planning purposes (e.g. for flood protection or environmental flow needs) and results of the Similkameen model provide opportunities to investigate these potential changes. In this section we briefly touch on these analyses, but the model results have potential for further exploration in this realm. To illustrate the subtle continuous nature of these changes, we have visualized the changes in extremes in a continuous manner rather than the 30-year climatological periods from the prior section.

Figure 4.5 illustrates the changes in the distribution of the day of year (DOY) of peak flow on the Similkameen River over time via a two-dimensional histogram. The results show that the primary peak flow dates during the spring freshet (e.g. DOY ~140) of the present day begins to degrade in the near future (e.g. 2030) and by 2050, peak flows are distributed throughout the early fall (e.g. DOY 300 or later) and throughout the winter and spring. Though the timing of the peak flow on the Similkameen Basin appears to change dramatically (and can be inferred in Figure 4.3), the magnitude of peak flows does not change substantially (Figure 4.6). The loess[15] smoothed line, which indicates approximately the mean annual flood, shows a slight decrease in peak flow by mid century, with a recovery to near present-day values by 2100.

Finally, we illustrated how the number of days per year with Similkameen River flows above 10000 ft^3/s changes over time. The 10000 threshold is important as it signifies backwatering conditions and thus changes operations of Zosel Dam. Figure 4.7 shows that the number of exceedance days gradually decreases through to the end of the century. This is likely due to the change from large volume, snowmelt driven, freshet flows to rainfall or rain-on-snow driven peak flows, which have a more rapid rise and fall for a peak event.

[15] Locally estimated scatterplot smoothing, a moving regression method for smoothing scattered data.

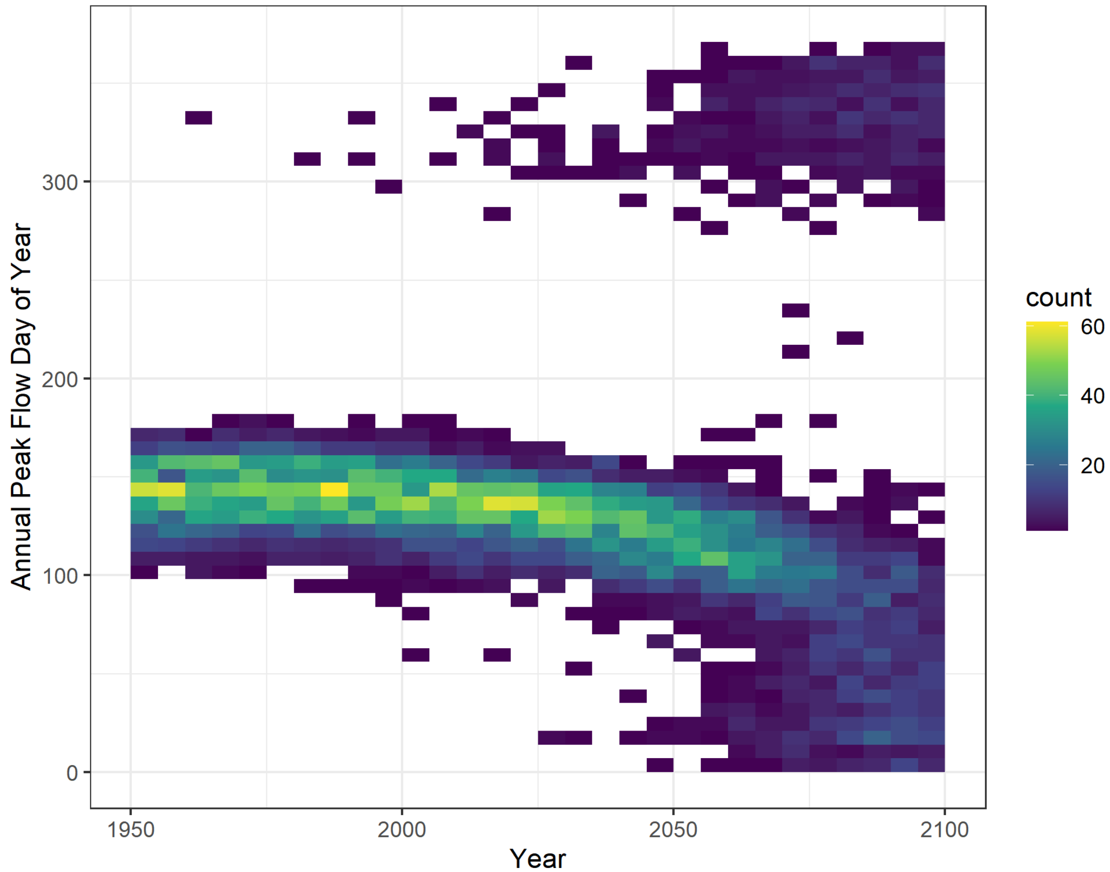

Figure 4.5 Day of year (DOY) of the peak flow on the Similkameen River near Nighthawk, WA for ensemble simulation (1950-2100). DOY is shown as a 2-d histogram with 5-year bins. Light colors indicate more common occurrences, dark colors indicate less common.

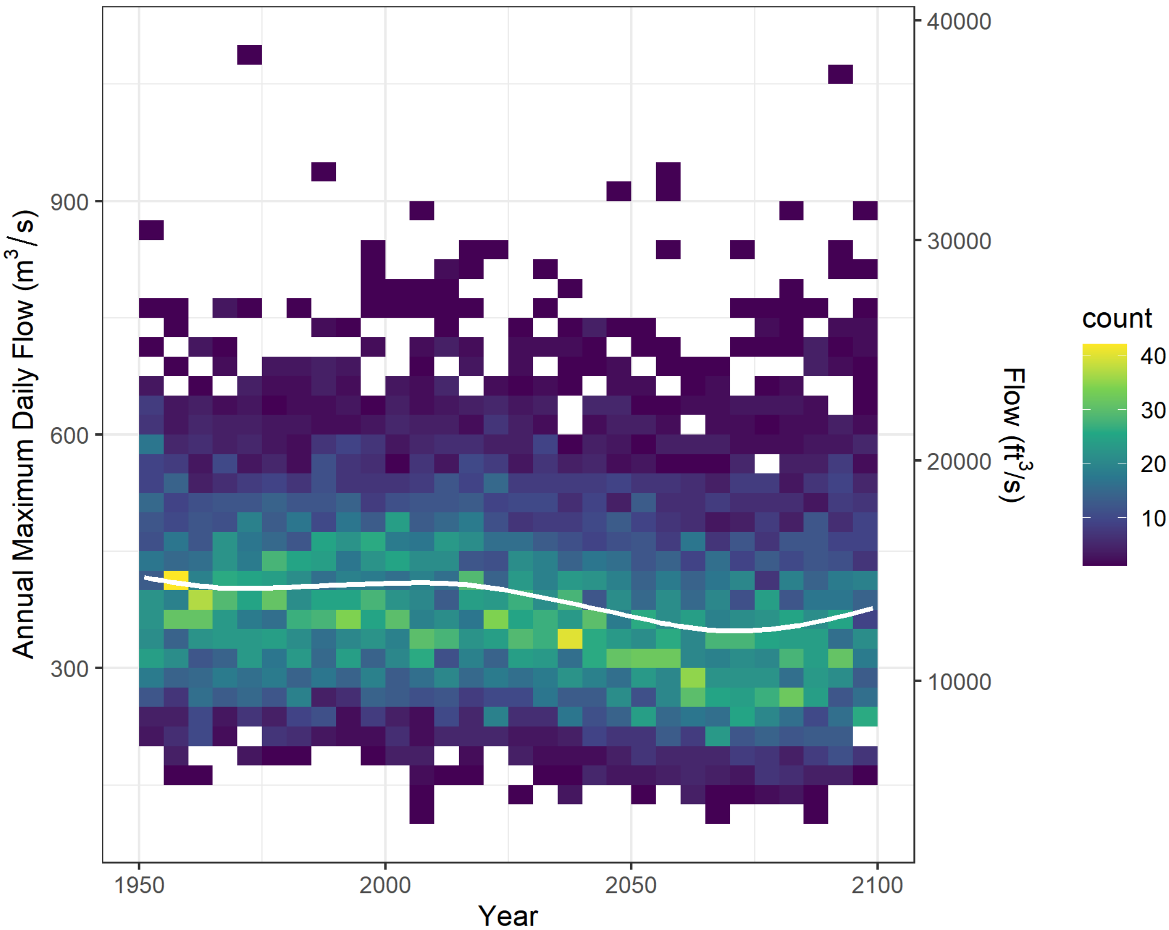

Figure 4.6 Annual maximum daily peak flow on the Similkameen River near Nighthawk, WA for ensemble simulation (1950-2100). Annual maximum daily flow is shown as a 2-d histogram with 5-year bins. Light colors indicate more common occurrences, dark colors indicate less common. White line is a loess smoothed value.

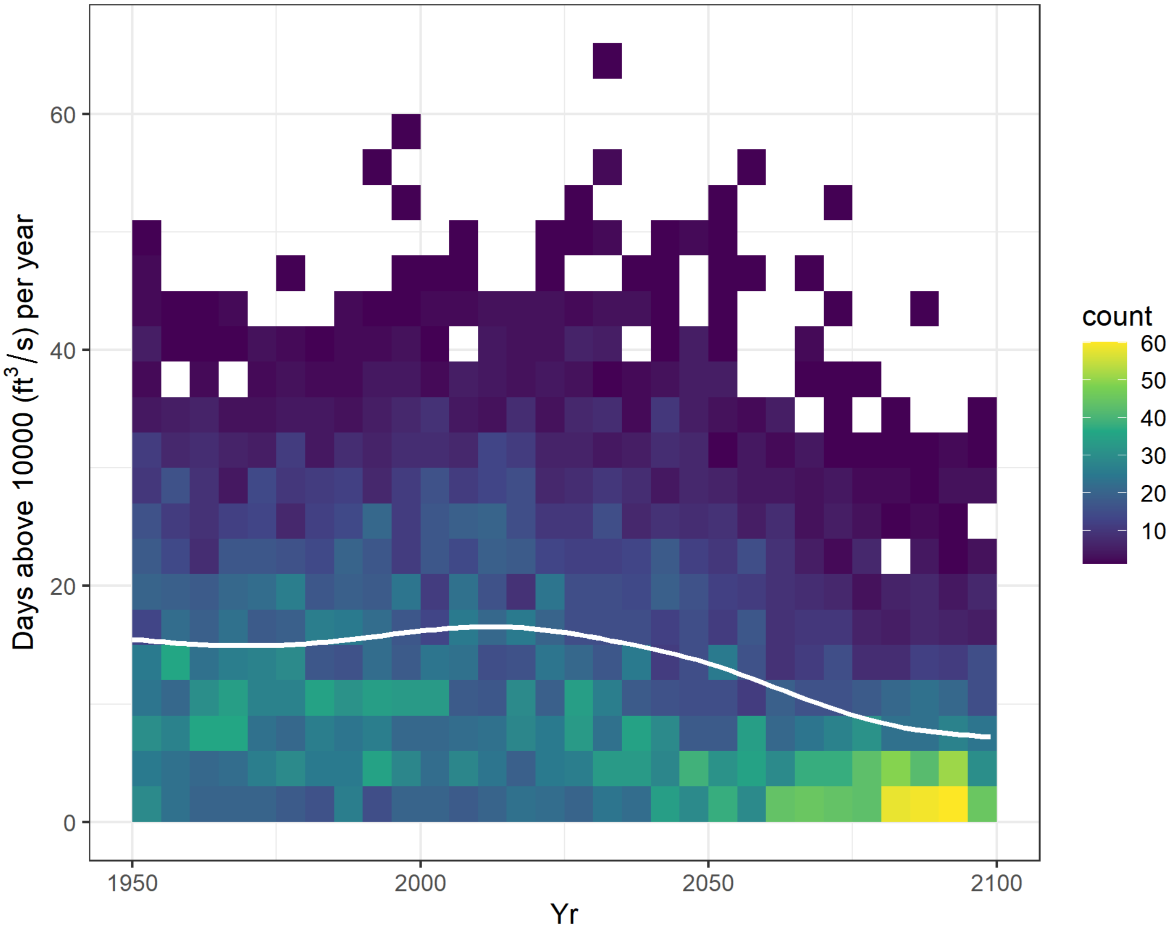

Figure 4.7 Number of days with flow greater than 10000 ft^3/s. Number of exceedance days are shown as a 2-d histogram with 5-year bins. Light colors indicate more common occurrences, dark colors indicate less common. White line is a loess smoothed value.

Extreme low flows were quantified through the 7-day low flow (i.e. the minimum 7-day mean flow for each year), and results are shown in Figure 4.8**.** The results indicate an increase in the 7-day low flow by mid-century, with gradual depletion towards the end of the century.

However, Figure 4.8 illustrates low flows at any time of the year, but summer low flows are likely more significant for planning purposes. Figure 4.9 shows that summer low flows on the Similkameen are expected to steadily decrease towards the end of the century. Currently, and predicted to the mid 21st century, annual low flows occur in winter (i.e. the loess line for Figure 4.9 is higher than Figure 4.8 until approximately 2040). However, as temperatures warm, it is predicted that winter flows will increase, while summer low flows will decrease.

As with the annual water yield, the visualized changes in extreme high and low flow magnitudes are slight; hence, further analysis (e.g. with a range of further climate forcings) would be prudent before taking final conclusions from these results.

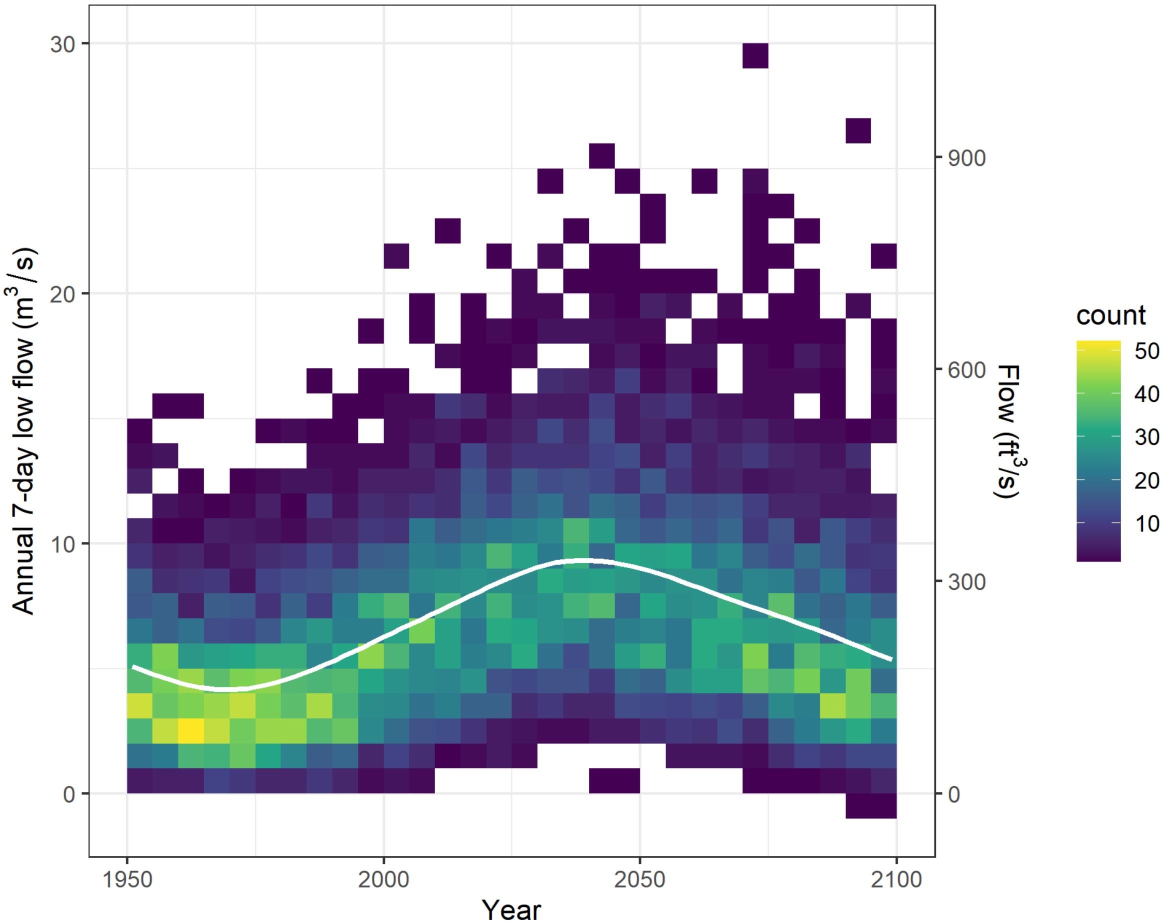

Figure 4.8 Annual 7-day low flow on the Similkameen River near Nighthawk, WA for ensemble simulation (1950-2100). Annual 7-day low flow is shown as a 2-d histogram with 5-year bins. Light colors indicate more common occurrences, dark colors indicate less common. White line is a loess smoothed value.

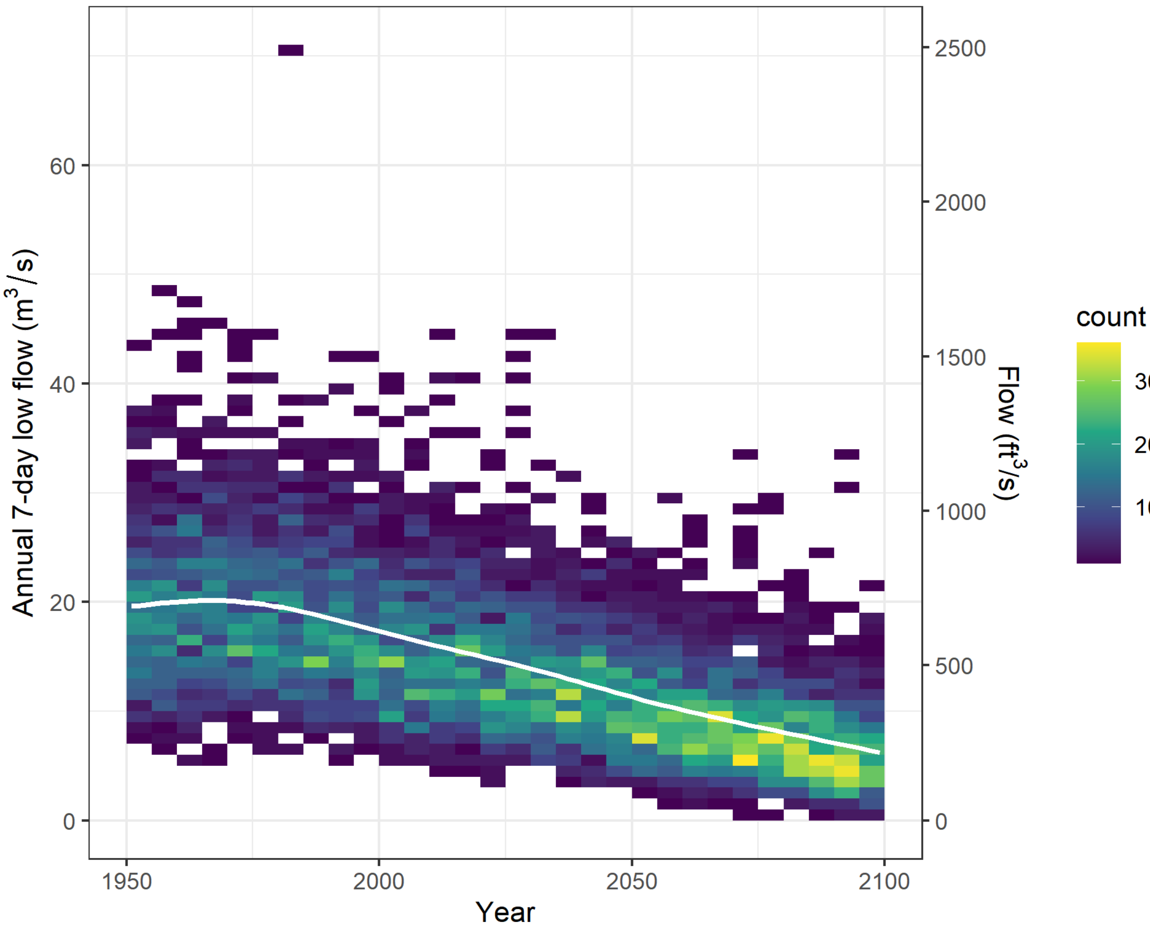

Figure 4.9 Annual 7-day low flow on the Similkameen River near Nighthawk, WA for ensemble simulation (1950-2100) summer periods (July - September). Annual 7-day low flow is shown as a 2-d histogram with 5-year bins. Light colors indicate more common occurrences, dark colors indicate less common. White line is a loess smoothed value.

4.3 Analysis of April to July Drought Data

The primary goal of this analysis was to investigate changes in the chances for meeting the April-July drought operations criteria on Osoyoos Lake (forecast April-July runoff volume for the Similkameen River near Nighthawk less than 1 million acre-feet of water). The Osoyoos Lake Board of Control seeks to understand if there are expected changes in the frequency of this drought criterion being met.

The changes in the annual hydrologic regime (Figure 4.3) have already illustrated that there is a significant shift in the annual distribution of water expected on the Similkameen River near Nighthawk, WA. Though the annual water yield only displays a moderate shift (increasing), the shape of the typical hydrograph is expected to change to a mixed regime more typical of the BC Coast mountains currently (though with a lower water yield).

The distribution of the freshet flow volume was first split into two periods, essentially, historical conditions (up to 2019) and future conditions (2020-2100). The probability density of freshet volumes is shown in Figure 4.10 and clearly illustrates the change in freshet volume by period. For the future period, the median year freshet volume is near the 1 million acre-feet threshold, and 48% of years are predicted to be below this threshold, as opposed to 18% for the historical period.

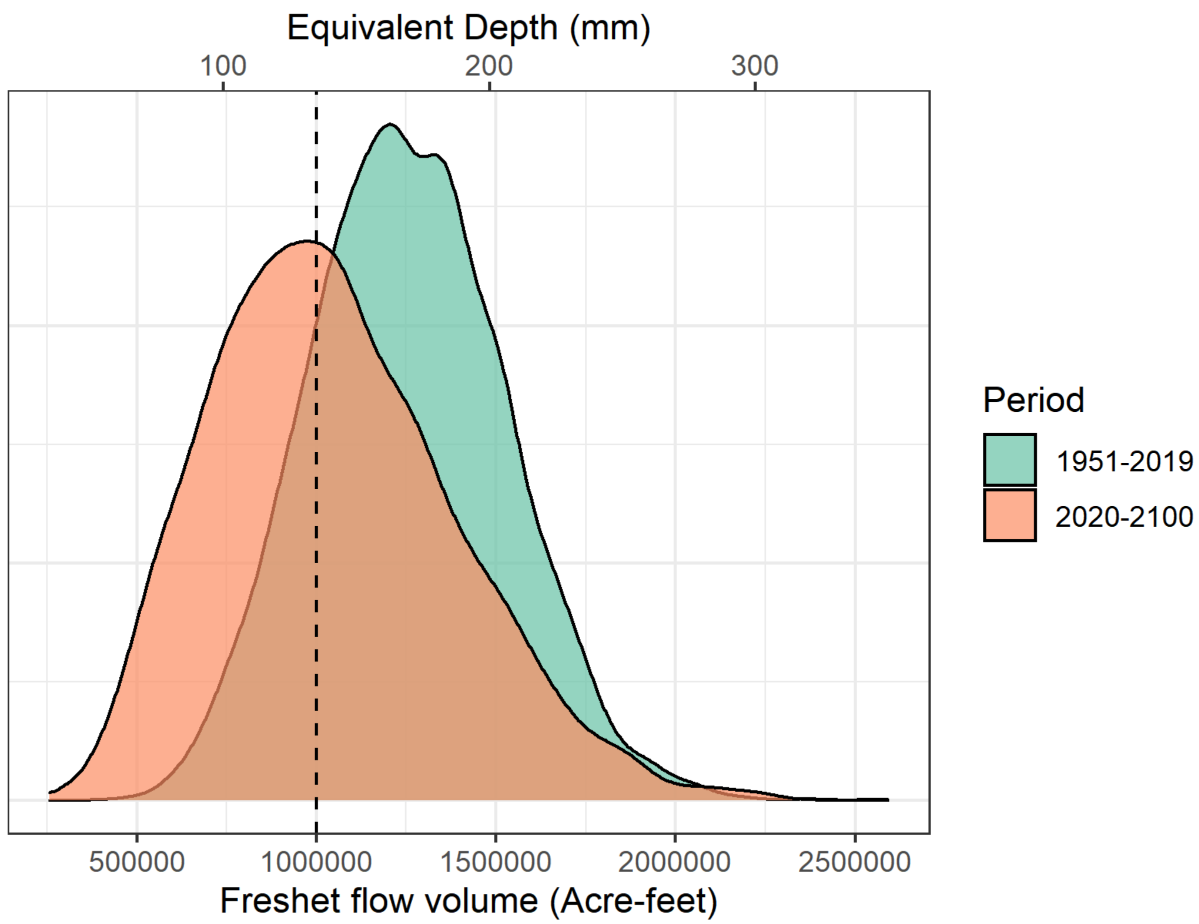

Figure 4.10 Probability density of April-July total flow volume for the Similkameen River near Nighthawk, WA, separated by historical and future period.

In addition to separation by historical/future periods, we further split the results by 30-year climatological periods, as in Section 4.2.2. These results are shown in Figure 4.11**.** The results indicate that the most substantial changes in the freshet volume distribution occur in the latter two climatological periods (after 2041). The percentage of years with April-July volumes less than 1 million acre-feet is shown in Table 4.2 and supports the idea that substantial changes occur in the 2041 and later periods, with a jump in frequency of 20% between 2011-2040 and 2041-2070.

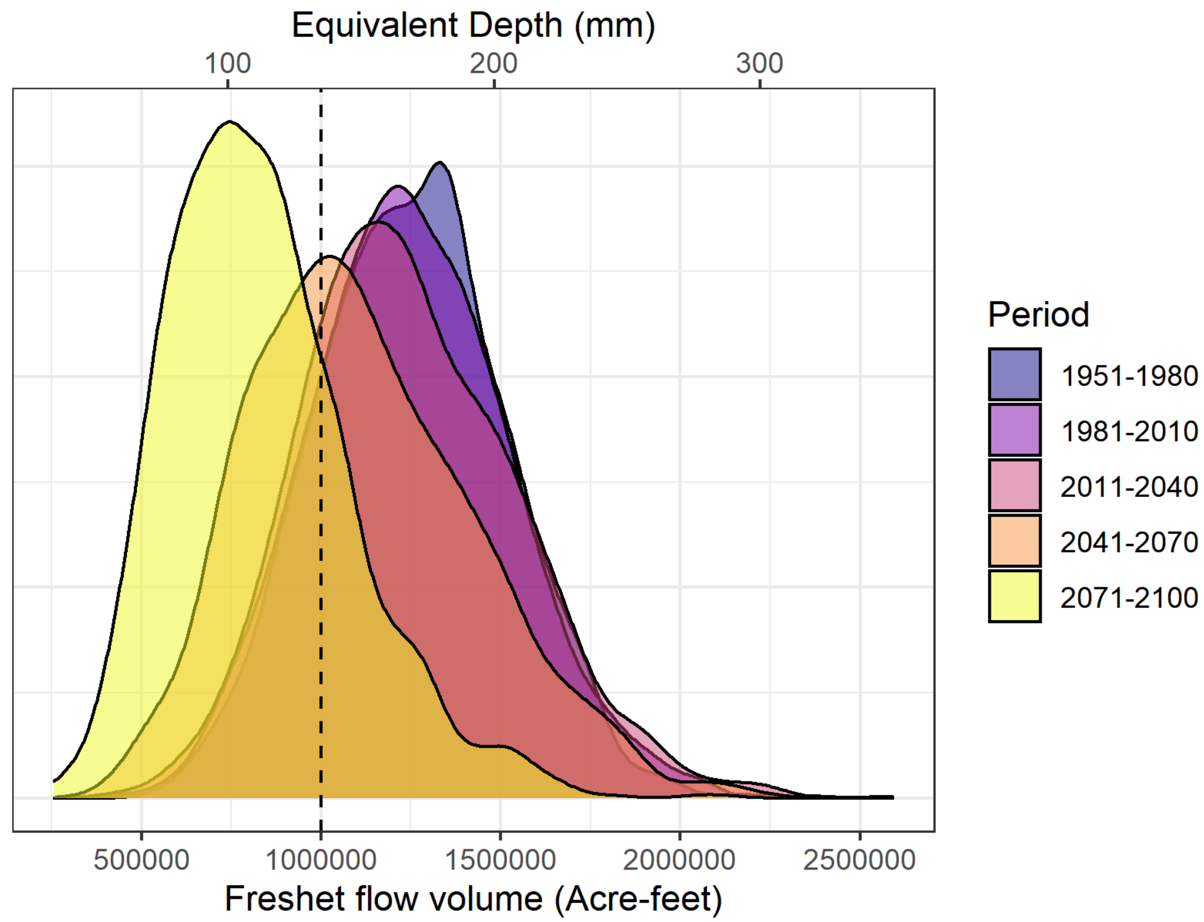

Figure 4.11 Probability density of April-July total flow volume for the Similkameen River near Nighthawk, WA, separated by 30-year climatological period.

Finally, we performed pairwise t-tests (using the same methodology as annual water yield) to compare the distributions of freshet flow volume (Table 4.3). As would be expected from the visualizations, results showed no significant difference between adjacent periods until the change between 2011-2040 and 2041-2070.

Table 4.2 Percent of years below the 1 million acre-foot drought criteria threshold for the Similkameen River near Nighthawk, WA.

	%
1951-1980	16
1981-2010	18
2011-2040	20
2041-2070	40
2071-2100	77

Table 4.3 Pairwise t-test results (p-values) for comparing distributions of April-July flow volume on the Similkameen River near Nighthawk by climatological period. E = 10^x. Bold numbers indicate p values for comparison with the prior climatological period.

	1951-1980	1981-2010	2011-2040	2041-2070
1981-2010	**1**	N/A	N/A	N/A
2011-2040	1	**1**	N/A	N/A
2041-2070	<1E-10	<1E-10	**<1E-10**	N/A
2071-2100	0	0	0	**<1E-10**

4.4 Summer flow volumes

Currently, the freshet flow volumes (whether forecasted at the beginning of the freshet, or observed by the end of July) are used as an indicator for lake inflows for the remainder of the summer, when flows on the Okanagan and Similkameen rivers are lowest and Osoyoos Lake levels generally reach their lowest (summer) levels. The previous section indicated that freshet flow volumes are expected to decrease towards the end of the 21st century. This is primarily due to a shift in the hydrologic regime away from being spring freshet dominated towards peak flows commonly occurring in winter and generally higher mid-winter flows.

In this section, we analyse the relationship between freshet (April-July) and late summer flow (August-September). If the freshet flow volumes are still a strong indicator of flows for the remainder of the summer, it is possible that the need for drought operations could still be forecasted via the freshet, if in a different manner than the 1 million acre-foot threshold. Figure 4.12 indicates that the summer flow volumes are expected to steadily decrease through the end of the century. This decrease in summer flows is more gradual than the pronounced shift in freshet volumes (Figure 4.11) and indicates that the relationship between freshet and late summer flows may change in the future.

To investigate this change, we calculated the Pearson correlation (Pearson R, where 0 indicates no correlation and 1 indicates a perfect correlation) between freshet and late summer volume, separated by climatological period. This result is shown in Table 4.4. Results indicate that the correlation between the two seasons is stable until the 2071, but less so for the later period, even while the corresponding volumes decrease. This result indicates that even if the freshet volume decreases substantially, it will still contain some predictive ability for the flow volumes for the remainder of the summer through 2071.

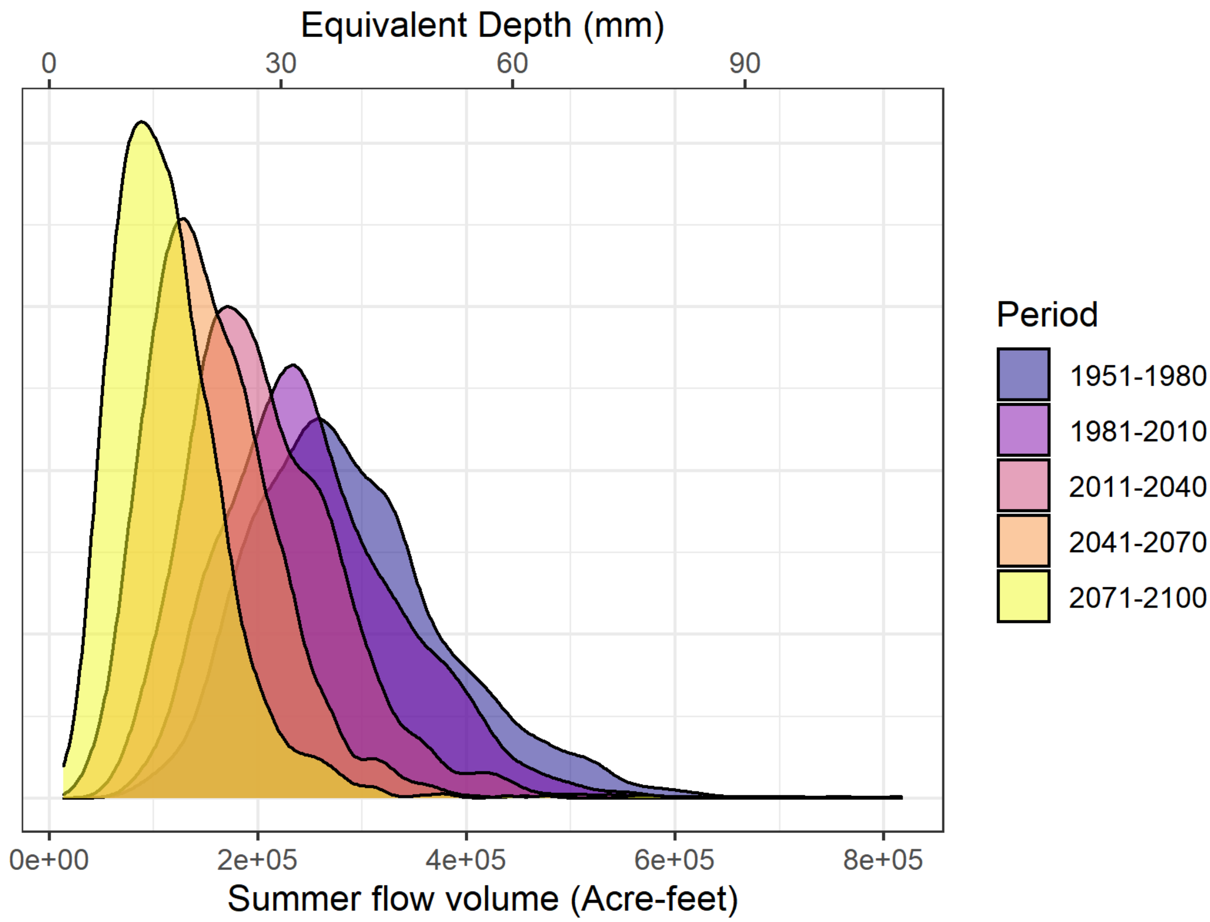

Figure 4.12 Probability density of August-September total flow volume for the Similkameen River near Nighthawk, WA, separated by 30-year climatological period.

Table 4.4 Pearson correlation (Pearson R) between freshet (April-July) and summer (Aug-Sep) flow volume, separated by climatological period.

	R
1951-1980	0.74
1981-2010	0.73
2011-2040	0.73
2041-2070	0.74
2071-2100	0.61

5 CONCLUSIONS

The Raven hydrologic model of the Similkameen Basin developed in this study has proven to be a skillful hydrologic model, particularly when analyzing results at the lowest gauge in the basin, WSC 08NL022 – Similkameen River near Nighthawk, WA. The calibration and validation results gave us confidence in using the model to carry out the IJC – Osoyoos Lake Board of Control's primary objective, to assess potential future changes in enacting drought operations on Osoyoos Lake.

Ensemble climate simulation using the CanLEADV1 dataset predicts substantial changes in the percentage of years triggering drought operations, particularly after the year 2040; however, these results appear to be primarily due to redistribution of water to the winter rather than an overall loss in water yield. The hydrologic regime is projected to shift to a mean hydrograph more similar to a coastal BC watershed, with low flows in summer, and raised flows throughout the winter due to more frequent winter rain events.

Analysis of the relationship between the freshet flow volumes and the flow volumes for the remainder of the summer indicate that, while the overall freshet and summer flow volume is expected to decrease, the predictive ability of the freshet does not appear to decrease until late in the 21st century. Thus, there may still be potential to use freshet flows as a part of an enhanced seasonal water supply forecast for Lake Osoyoos and the Okanogan River; however, the predictive ability of the snowpack and the spring freshet is forecast to be diminished.

The redistribution of water supply on the Similkameen River (increasing winter flows and decreasing summer flows) means that potential changes to both forecasting and management of the Osoyoos Lake system should be explored. The predicted diminished relationship between the freshet and summer flow volumes on the Similkameen River imply that there may also be a diminished correlation between Osoyoos Lake levels and the Similkameen River in the future. This relationship should be explored during Phase 2 of this analysis.

5.1 Project limitations

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

- The hydrologic model used in this analysis is a conceptual model, based primarily on calibrated parameters. While HBV-EC has been used for climate projections in British Columbia regularly, the end user should recognize that simulation results are extrapolated outside of the conditions for the calibration period (e.g. a warmer and wetter future than any climate experienced in the calibration period) and hence uncertainty is increased.
- Meteorological forcing data (the Okanagan-Similkameen climate data) has been provided by an outside source, and hence has not been quality controlled by NHC. Thus, source data errors cannot be identified or corrected by NHC.
- The hydrologic model does not take into account potential future land use changes within the watershed (e.g. increased population or agriculture, or major forest disturbance). However, future iterations of the model could incorporate these projections

- The CanLEADV1 dataset is an ensemble of a single climate model output (CanESM2) which has been shown to be a warmer and wetter model output than other models (NHC, 2020). While this dataset is not an outlier, this result should be considered in that context, and the reader should recognize that some results (e.g. small changes in future water yield) may be different with a different climate projections dataset.
- A single RCP (8.5) has been used, which is currently identified as a high baseline scenario for a carbon pathway, dependent on great expansion of coal usage in the future[16]. While no likelihood of one RCP over another has been assigned, RCP 8.5 represents a future in which no mitigation efforts are undertaken[17]. While useful as a risk assessment tool, the RCP 8.5 scenario could be considered a pessimistic view of the future, and assessment of a lower RCP (6 or 4.5) may be needed as the direction that climate action and mitigation follows becomes clearer in the future.
- Water demand projections are based on population trend forecasts, and a relationship between demand and population. Unforeseeable events may render these forecasts or relationships incorrect.

5.2 Future recommendations

Future integration with the Okanagan Basin model will help to illustrate how upstream inflows to Osoyoos Lake will interact with the modelled changes to flows on the Similkameen River. These changes may provide further guidance on updates to the summer lake level and Okanogan River flow forecasting system. Additionally, integration may provide guidance on how to alter upstream Okanagan system operations to assist in meeting environmental flow needs on the Okanogan River in a future with potentially lower low flows.

Along with the planned integration of the Okanagan and Similkameen Basin models, future work should focus on exploring options for seasonal baseflow forecasting that do not solely rely on the winter snowpack. While the snowpack is currently the most important predictor for summer flows in most of Western North America, it appears that this predictive ability will decrease in the future.

The current state of weather forecasting does not allow for long term forecasts of precipitation, so alternative seasonal forecast options will likely need to focus on basin-level indicators of soil moisture and groundwater, along with ensemble seasonal forecasting of Similkameen River flows in order to obtain a probabilistic forecast of summer flows. On the nearby Kettle River, Allen et al (2004) estimated a groundwater exchange of roughly 0.5 m^3/s (either positive or negative) with river flows. While this is a fraction of even the average 7-day low flow on the Similkameen (~9 m^3/s), there may be some predictive utility in forecasting the direction of flux between groundwater and river flows during the summer months.

[16] https://www.carbonbrief.org/explainer-the-high-emissions-rcp8-5-global-warming-scenario

[17] https://www.nature.com/articles/d41586-020-00177-3

Finally, the focus of this project was on changes in the drought operations criteria on the Similkameen River; however, detailed hydrologic modelling using ensemble climate projections provides a rich dataset for analysis of potential changes in the basin. The detailed hydrologic model contains significant potential for further analysis, beyond what is covered in this project alone. For example, subbasin by subbasin analysis, more specific investigations into changes in extreme peak flows or low flows, and investigation of changes in hydrologic processes (e.g. evapotranspiration) are all possible. Additionally, the developed model will allow for future extensions such as investigation into potential changes in landcover or water demand and future expansion of climate model forcings and RCPs.

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APPENDIX A

WATER DEMAND – ASSOCIATED ENVIRONMENTAL, INC.

Associated Environmental

TECHNICAL MEMORANDUM

Issue Date:	March 31, 2021	**File:**	
To:	**Northwest Hydraulic Consultants Ltd.**	**Previous Issue Date:**	March 2, 2021
From:	Andras Szeitz, M.Sc., GIT; Drew Lejbak, M.Sc.		
Client:	Northwest Hydraulic Consultants Ltd.		
Project Name:	Osoyoos Lake Climate Change Vulnerability: Phase 1 - Similkameen Basin Hydrologic Model	**Project No.:**	2020-8592.000
Subject:	Summary of Methods used to Derive Historic and Future Water Demand Estimates for the Similkameen River Watershed		

1 INTRODUCTION

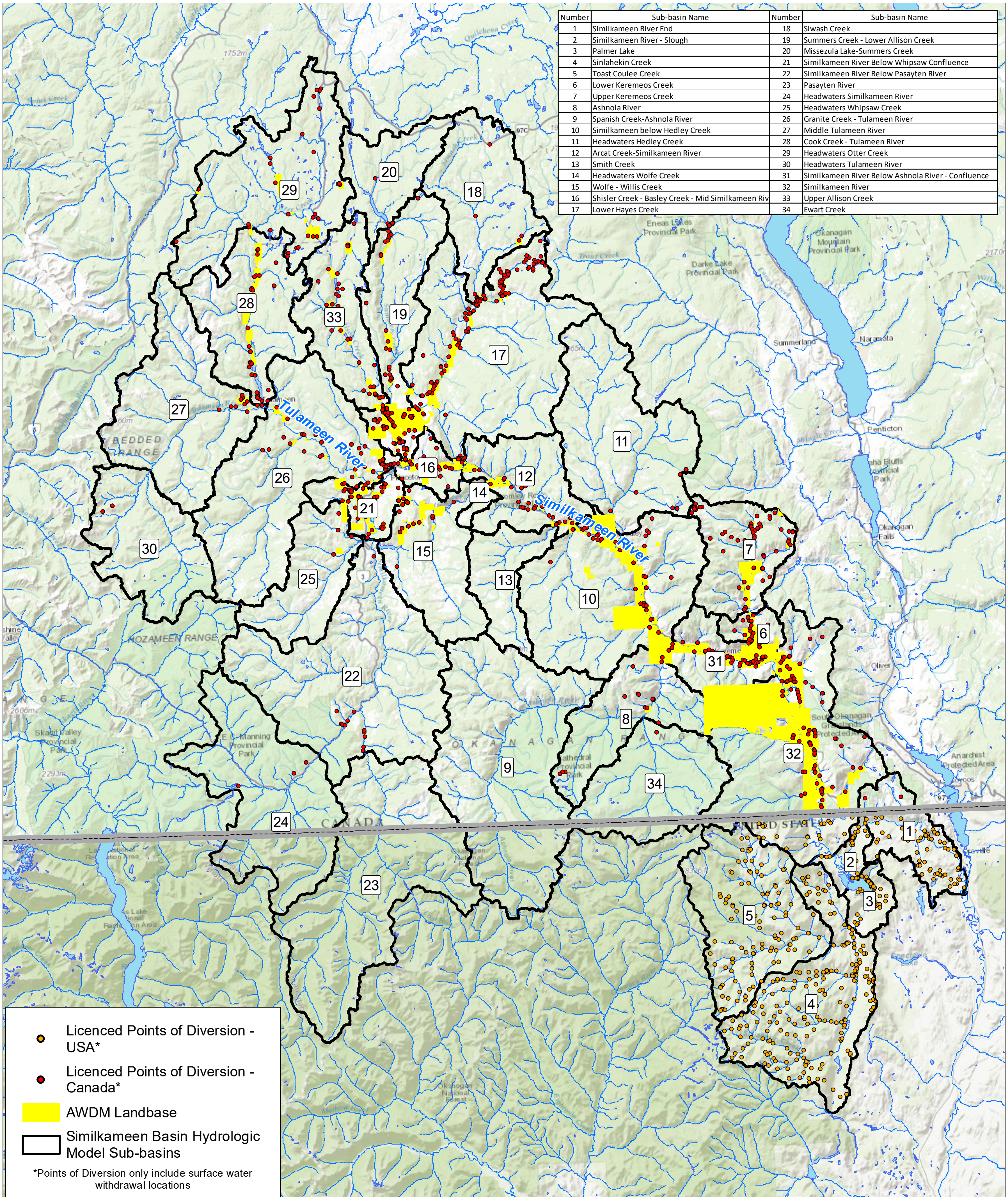
To support Northwest Hydraulic Consultants Ltd. (NHC) with the development of a hydrologic model for the Similkameen River watershed (the Watershed), Associated Environmental Consultants Inc. (Associated) provided historic and future daily water demand estimates for the Watershed. These estimates are required to support residual streamflow[1] modelling to assess climate change vulnerability of Osoyoos Lake. The climate change vulnerability assessment focuses on consideration of low streamflow and drought conditions, and associated drought triggers included within the Osoyoos Lake Supplementary Orders of Approval. Water demand estimates are needed to ensure accurate representation of streamflow during low flow periods in the Similkameen River watershed hydrologic model.

This technical memorandum provides a summary of water demand estimates developed by Associated for the Watershed. Estimates were generated on a sub-basin level, based on sub-basin delineations developed by NHC (Figure 1-1). Daily water demand estimates were generated for a historic period (1945-2012) and four different future climate scenarios for the period 2013-2100. Land use, irrigation efficiency, and crop types were considered constant over the entire study timeframe (1945-2100), partly due to limited information on historic changes and future land use and agricultural planning within the Canadian and US portions of the Watershed.

2 AVAILABLE WATER DEMAND INFORMATION

This section provides an overview of available historic and future water demand information for the Watershed. Since a portion of the Watershed is located south of the BC/United States border, different information sources were used to provide information for different sub-basins, as needed.

[1] Residual streamflow is the remaining streamflow after water withdrawals have been made from the natural streamflow.



Number	Sub-basin Name	Number	Sub-basin Name
1	Similkameen River End	18	Siwash Creek
2	Similkameen River - Slough	19	Summers Creek - Lower Allison Creek
3	Palmer Lake	20	Missezula Lake-Summers Creek
4	Sinlahekin Creek	21	Similkameen River Below Whipsaw Confluence
5	Toast Coulee Creek	22	Similkameen River Below Pasayten River
6	Lower Keremeos Creek	23	Pasayten River
7	Upper Keremeos Creek	24	Headwaters Similkameen River
8	Ashnola River	25	Headwaters Whipsaw Creek
9	Spanish Creek-Ashnola River	26	Granite Creek - Tulameen River
10	Similkameen below Hedley Creek	27	Middle Tulameen River
11	Headwaters Hedley Creek	28	Cook Creek - Tulameen River
12	Arcat Creek-Similkameen River	29	Headwaters Otter Creek
13	Smith Creek	30	Headwaters Tulameen River
14	Headwaters Wolfe Creek	31	Similkameen River Below Ashnola River - Confluence
15	Wolfe - Willis Creek	32	Similkameen River
16	Shisler Creek - Basley Creek - Mid Similkameen Riv	33	Upper Allison Creek
17	Lower Hayes Creek	34	Ewart Creek

Associated Environmental

PROJECT NO.: 2020-8592.000.001
DATE: March 2021
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FIGURE 1-1: SIMILKAMEEN RIVER WATERSHED OVERVIEW

Northwest Hydraulic Consultants

Osoyoos Lake Climate Change Vulnerability: Phase 1 – Similkameen Basin Hydrologic Model

2.1 Canadian Water Demand

The primary sources of water demand in the Canadian portion of the Watershed varied between the sub-basins, but irrigation and water licensed for storage, land improvement, and/or commercial/industrial use form the largest sources of water demand. The sources of current water demand information within BC include water licences and modeled water demands from the Agriculture Water Demand Model (AWDM) (Figure 1-1). The AWDM is a computer model that provides estimates of agricultural (i.e., irrigation and stockwatering) water demand for select areas across BC including the Watershed[2]. Since actual water use records from water suppliers within the Watershed are limited, the AWDM provides the best available estimate of agricultural water demand for the Watershed and was used herein.

The AWDM can provide estimates of future agricultural water demand by making use of gridded datasets of future climate projections. Accordingly, future estimates of agricultural water demand for the Canadian portion of the Watershed were obtained from the AWDM (from RHF Systems Ltd. – the model manager) using downscaled gridded climate datasets generated by NHC[3]. Due to the lack on information on groundwater-surface water interaction within the Watershed, only agricultural and stockwatering AWDM estimates sourced by surface water sources were considered[4].

To estimate non-agricultural water demand within the Watershed, all active water licences (i.e., storage, waterworks, domestic, and conservation licences) were assumed to be fully used (i.e., the total licensed volume is used annually). However, due to the absence of future projections for non-agricultural water demand, these licensed amounts were assumed constant into the future.

2.2 United States Water Demand

For the United States portion of the Watershed, the primary source of water demand is irrigation use, with smaller demand needed to support waterworks[5], domestic, industrial, aquaculture, mining, and livestock uses. Surface water withdrawals estimated for Okanogan County were available from previous work by the USGS (2021)[6]. Waterworks are defined as water supply by a utility/supplier to a municipality or distribution and is separately from domestic water use. Available estimates included per capita daily waterworks and domestic water use, daily industrial, aquaculture, mining, and livestock water use, and annual irrigation rates and irrigated land area for Okanogan Country (Figure 1-1). Water

[2] Van der Gulik, T., Neilsen, D., Fretwell, R., and A. Petersen. 2012. Agriculture Water Demand Model: Report for the Similkameen Watershed. Funded by Canada-British Columbia Water Supply Extension Program, April 2012.

[3] Climate datasets were re-projected by Associated to allow ingestion to the AWDM.

[4] RHF Systems Ltd. 2020. Agriculture Water Demand Model – Similkameen Valley AWDM Modeling. Prepared for Associated Environmental Consultants.

[5] Referred to as public-supply by USGS (2021) but redefined here to be consistent with Canadian terminology..

[6] United States Geological Survey (USGS). 2021. USGS Water Use Data for Washington. https://waterdata.usgs.gov/wa/nwis/wu

rights documents were obtained from the Washington State Department of Ecology (DOE)[7,8]. The water rights documents include information regarding the rights' permitted water use purposes.

Since the AWDM does not include the United States portion of the watershed, future water demand volumes in the US were derived from the information provided by the USGS (2021) and the DOE water rights but made use of AWDM estimated irrigation patterns for the Canadian portion of the Watershed to include future climate conditions on irrigation requirements. Increases in water demand because of future population growth was also considered for domestic uses.

3 METHODS

Daily water demand estimates were generated for the historic (i.e., calibration) period (1945-2012) and four different future climate scenarios for the period 2013-2100. Details regarding the processing of the water demand data for the historic and future water demand periods are presented in the following sections.

3.1 Historic Water Demand

<u>Canadian Land Area</u>
Associated obtained agricultural water demand estimates from RHF Systems Ltd. who ran the AWDM for the 1945-2012 historic period, based on historic gridded climate data generated by NHC (Fretwell 2020). Water licence information was summarized as follows:

- Water licences were grouped by sub-basin based on water use purpose as defined by the BC Ministry of Forests, Lands, Natural Resource Operations, and Rural Development (2016)[9].
- Storage licences assumed there was no carry over storage from year to year and annual licensed volumes were diverted into storage following the natural streamflow pattern of the Similkameen River and/or other nearby streams monitored by the Water Survey of Canada. Releases from storage were assumed constant over the period of April 1 to September 30.
- Water licences for run-of-river type power generation were omitted.
- Waterworks and domestic annual licensed volumes were distributed according to a monthly distribution based on actual water use records from Hedley Improvement District (Summit 2015)[10]. A Loess function was fitted to the monthly distributions and a daily percentage calculated to convert the monthly distribution to daily demand.
- All water demand purposes (e.g., agricultural, storage) by sub-basin and per day were summed to produce a total daily demand (m^3) and converted to a total water demand rate (m^3/s).

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[7] Washington State Department of Ecology (DOE). Geographic Water-right Information System. Data retrieved June 2020.

[8] Washington State Department of Ecology (DOE). Water Right Tracking System. Data retrieved June 2020.

[9] Natural Resource Online Services. 2016. Definitions for Water Use Purposes and Categories of Water Use Purposes. FrontCounter BC.

[10] Summit Environmental Consultants Inc. (Summit). 2015. Similkameen Watershed Plan – Phase 2: Water Supply, Quality, and Groundwater – Surface Water Interaction Technical Studies. Prepared for the Regional District of Okanagan-Similkameen, June 2015.

Of note, all water licences were assumed constant over the historic period and individual license priority dates were not considered. Because the scope of hydrologic model calibration was at the Watershed scale, 50% of licences are old (i.e., 1960 or older), and streamflow records available for model calibration vary, licence introduction over time was deemed to have limited influence on the resultant residual streamflow modelling. Also, due to the lack of available information, no historic land use changes over time were considered and the land base available within the AWDM was considered representative of historic and future agricultural land areas and practices.

United States Land Area

The USGS (2021) provided average daily water demands and annual irrigation rates for the Unites States portion of the Watershed. While a constant average daily rate may be reasonable to assume for waterworks, domestic, industrial, mining, aquaculture, and stockwatering water use, it is not reasonable for irrigation use. The following summarizes how water demand estimates were produced for the Similkameen River sub-basins located in the United States:

- The most recent US Census Bureau census tract population density (people/km^2) data (2010 census) was used to estimate the total population living within each United States sub-basin area (Figure 1-1). Three sub-basin population estimates that were unrealistically high (e.g., predominantly forested sub-basins with limited development but estimated population > 200 people) were adjusted using aerial photography surveys of the number of buildings or homes.
- Okanogan County daily per capita waterworks and domestic water use was multiplied by the sub-basin populations to obtain total daily demands per sub-basin.
- Water rights were summarized by sub-basin and the reported irrigated land area associated with water rights with irrigation purposes was summed. For sub-basins where the total reported irrigated land area from water rights deviated from the Okanogan County average irrigated land area (USGS 2021), the irrigated land area was estimated from aerial photography. This approach is consistent with methods used by Associated to estimate irrigation water demands for FLNRORD to support the issuance of water restrictions under drought conditions in BC.
- The sub-basin irrigated land area was multiplied by Okanogan County long-term average irrigation rate to estimate total annual sub-basin irrigation demand. The annual irrigation rates reported by the USGS (2021) were fairly consistent through time despite USGS reported changes in irrigated land area over the same period. Annual irrigation demand per sub-basin was then distributed to daily demands using the historic average daily irrigation pattern derived from the AWDM output for the Canadian sub-basins.
- The permitted water rights uses within each sub-basin were summarized and compared to the water uses reported by the USGS (2015). Water uses reported by USGS (2015) that were absent from the sub-basin permitted uses (e.g., mining) were omitted. Average daily use for livestock, aquaculture, industrial, and commercial purposes were scaled according to the land area ratio of the sub-basin to Okanogan County for the respective sub-basins in which those water uses have issued water rights.
- Total daily water demand (m^3) for all purposes was calculated and converted to a total water demand rate (m^3/s).
- Sub-basins with zero water rights were assumed to have no water use.

Like the Canadian Land Area, water rights priority dates were not individually considered. Due to the lack of actual water use information for the US portion of the watershed, the average irrigation and waterworks/domestic per capita rates were assumed representative of the full historic period. Upon review of available USGS and DOE information, the irrigation rates and waterworks/domestic per capita rates did not significantly vary over time, so this assumption was deemed reasonable.

3.2 Future Water Demand

Domestic water use was adjusted by rounding estimates of annual population growth rates to values of 1% and 0.5% in the Canadian and United States regions, respectively, for the future period (i.e., 2013-2100).

Waterworks water use was assumed to stay constant across the modelled period, as the existing water licences were assumed to be of sufficient volume to meet water demands up to 2100. Specific information on how waterworks licensed use may change in the future is unknown at this time, so the available licensed volume was deemed sufficient to meet future needs. Similarly, all other water licensed use (e.g., commercial, industrial) was assumed to stay constant.

Full period (1945–2100) agricultural and stockwatering water demands[11] were generated using four Global Circulation Model (GCM) outputs, named qdm1, qdm2, qdm15, and qdm17, developed and provided by NHC. The qdm datasets 1 and 2 are representative of average future climate conditions, while qdm 15 and 17 represent the warmest and coldest May – September average daily maximum temperature in the year 2071 and onwards[12]; all future climate datasets are developed under RCP8.5. Associated obtained water demand estimates for the Canadian sub-basins from the AWDM using the four GCM outputs provided by NHC (Fretwell 2020).

The GCM outputs specifically cover the years 1950–2100 rather than the full period (1945–2100). To address this gap (1945-1949), the Watershed averaged daily AWDM demand estimates for 1950–1979 were used to generate agricultural and stockwatering demand estimates for 1945-1949. Associated judged the period of 1950-1979 to be generally representative of the climate and water use trends generated by the AWDM and can be used to estimate demands for the 1945-1949 period.

Since the AWDM does not include the United States portion of the Watershed, irrigation demands for the United States sub-basins were adjusted for future conditions using the future AWDM results for the Canadian watershed portion as follows:

- The total daily water demands from the AWDM were calculated for the 'normal' period of the 30 years prior to the end of the historic period (i.e. the 30-year period 1983–2012). This served as the 'baseline' time period for calculating future irrigation demand.
- For each year of future AWDM demand (2013–2100), the total daily AWDM water demand and its percentage change over baseline was calculated.

[11] Stockwatering water demands do not increase into the future, as the AWDM assumes a constant number of livestock for the historic and future periods

[12] Trubilowicz, J. Environmental Data Scientist, Northwest Hydraulic Consultants Ltd. February 5, 2021. Personal communication (email) with Andras Szeitz of Associated.

- The future year percentage change was then applied to each United States sub-basin to estimate future irrigation demand.

3.3 Water Demand Output Files

The daily sub-basin water demand results were compiled into two datasets for inclusion in the Raven hydrologic model, one for water demands, and one for storage releases. The water demands, including storage diversions, were written to Raven format .rvt files using the 365-day year convention of the GCM output datasets. Storage releases were also written to .rvt files using the same 365-day year format. The water demand .rvt files used the Raven hydrograph handling method '*:IrrigationDemand*', which removes the demand volume for each timestep from the corresponding sub-basin. The storage release .rvt files used the Raven hydrograph handling method '*:BasinInflowHydrograph*', which adds the storage release volume for each timestep to the corresponding sub-basin's inflow.

3.4 Key Assumptions

Due to the cross-jurisdictional nature of the Watershed and the different information sources available, the assumptions previously used to develop water demand estimates for the Watershed by Summit (2015) were adjusted and applied for the Watershed as follows:

- All Canadian and US water licences/rights were applied for the period 1945-2012 and individual priority dates were not considered due to the limited information on no historic land use changes and the general small volumes of licenses (introduced over time) in comparison to streamflows at the Watershed scale.
- All Canadian water licensed volumes (except irrigation and stockwatering) are fully utilized for the historic and future periods.
- Water licences for land improvement and commercial or industrial use withdraw water at a constant daily rate unless a given licence has a specific licensed use period.
- Storage licences assumed a diversion pattern into storage that followed the general streamflow pattern of the Watershed (and/or selected sub-basin) during the period of licensed diversion into storage. Releases from storage were assumed constant over the period of April 1 to September 30, which is generally consistent with licensed release periods.
- Canadian waterworks and commercial/industrial water licensed volume will remain constant in the future, which assumes that existing licensed amounts are sufficient to meet future needs within the respective areas (due to lack of available information to assess otherwise).
- The AWDM assumes no change in cropping, irrigation methods/efficiencies, or livestock numbers for future water demand.
- Groundwater use is not included in either Canadian or United States water demand due to the lack of information on groundwater well use, hydraulic connectivity of wells to the sub-basin watercourses, and limited aquifer representation within the Raven hydrologic modelling framework.
- The reported current Okanogan County surface water use represents 'actual' water use, rather than licensed volumes that may or may not be fully used.

- The regional Okanogan County-averaged water use rates (e.g., domestic per capita use, annual irrigation rate [m per hectare][13]) are representative of the Similkameen land area in Okanogan County.
- The USGS (2021) reported historical water use rates for waterworks per capita use, domestic per capita use, irrigation rates and livestock demand. These rates did not change significantly or indicate trends through time, so the long-term average water use rates were used. The average water use rates for waterworks per capita use, domestic per capita use, irrigation rates, and livestock demand reported by the were assumed to be representative of future demands.
- Population growth rates of 1% and 0.5% were assumed for the Canadian and United States populations[14,15], respectively, for the years 2013–2100. These growth rates were applied to domestic water licensed amounts (Canada) and reported domestic per capita water use (US) for future periods.

NHC is using the Raven hydrologic modelling framework (Raven) for streamflow modelling. Raven allows considerable flexibility around watershed hydrologic modelling, including the implementation of water extractions to incorporate irrigation demands as it does not model it directly. Raven allows water to be extracted from, or added to, individual sub-basins in a number of ways. Based on our knowledge of Raven and to facilitate water demand implementation in NHC's model, the water demand estimates handle the timing of water extractions and releases as follows:

- All water demands (i.e., off-stream use and diversions to storage) are removed from individual sub-basins using the *:IrrigationDemand* command. Using this command, water is extracted from individual sub-basins as long as there is sufficient water available (i.e., enough water to prevent zero flow in the creek). If insufficient flow exists within a sub-basin, Raven will report "unmet" demand (i.e., the amount of water that could not be extracted, since the flow in the creek was already zero).
- Releases from storage are added back to individual sub-basins using the *:BasinInflowHydrograph* command. This command is not conditional on available streamflow volumes.

This approach assumes that modelled streamflows within each sub-basin are sufficient to satisfy all demands via *:IrrigationDemand* and that no "unmet" demand for any sub-basin is reported by Raven. It furthermore acknowledges precipitation for irrigation requirements are accounted for in the water demands estimated by the AWDM, as Raven accounts for precipitation in evapotranspiration and runoff generation processes.

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[13] Irrigation rate as a depth of water per hectare.

[14] Ip, F., and S. Lavoie. 2019. PEOPLE 2020: BC Sub-Provincial Population Projections. BC Stats.

[15] Okanogan County Office of Planning and Development. 2020. Okanogan County Comprehensive Plan – Appendix 10.

4 ESTIMATED WATER DEMANDS AND TRENDS

The estimated annual total water demands, including irrigation and licenced water demands, for the entire Watershed for the historic period (using the historic and downscaled GCM climate data outputs provided by NHC) are provided in Figure 4-1. The irrigation demands estimated by the AWDM using the GCM datasets produced irrigation demands from 1950 onwards and are plotted accordingly; however, the irrigation demands for the GCM datasets for 1945-1949 were estimated due to the GCM record beginning in 1950. While the calibration dataset and GCM datasets are not directly comparable due to different provenances, the water demands derived from the GCM datasets generally follow the trend and magnitude of variability in the demands derived from the calibration dataset. The climate projection datasets appear to follow the general trend of the calibration dataset demands well. The demands are provided as a depth equivalent (watershed total demand volume / watershed area). Interannual variability is present but demands are fairly constant overall from 1950 until the early 1990s, at which point there appears to be a change in the demands trend.

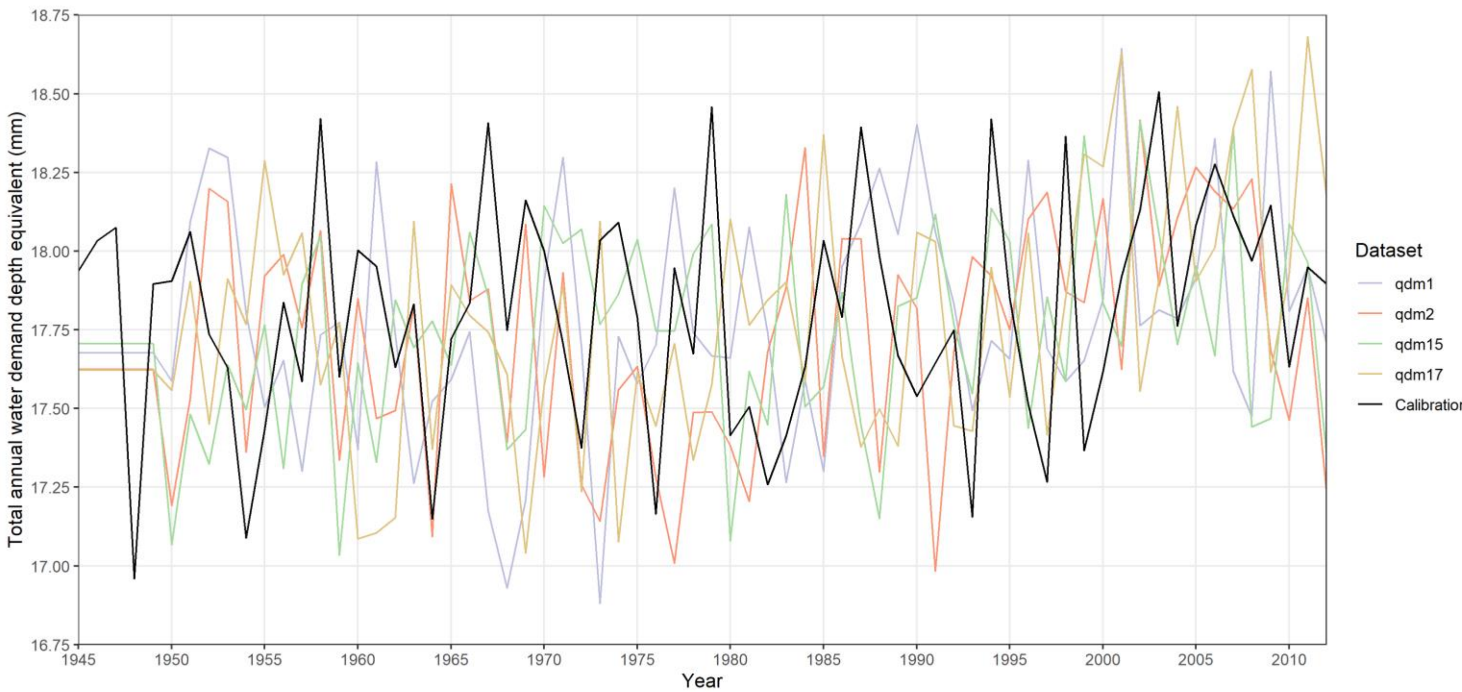

Figure 4-1 – Annual watershed depth equivalent water demands for the historic (calibration) dataset and climate projection datasets for the historic period 1945 – 2012.

The full period (1950 – 2100) estimated water demands from the AWDM are provided in Figure 4-2 grouped by month and five 30-year modelling periods (1951-1980, 1981-2010, 2011-2040, 2041-2070, and 2071-2100). The individual qdm distributions are lumped together for consistency with NHC's lumped ensemble analysis[16].

[16] Trubilowicz, J. Environmental Data Scientist. Northwest Hydraulic Consultants Ltd. March 29, 2021. Personal communication (email) with Andras Szeitz of Associated.

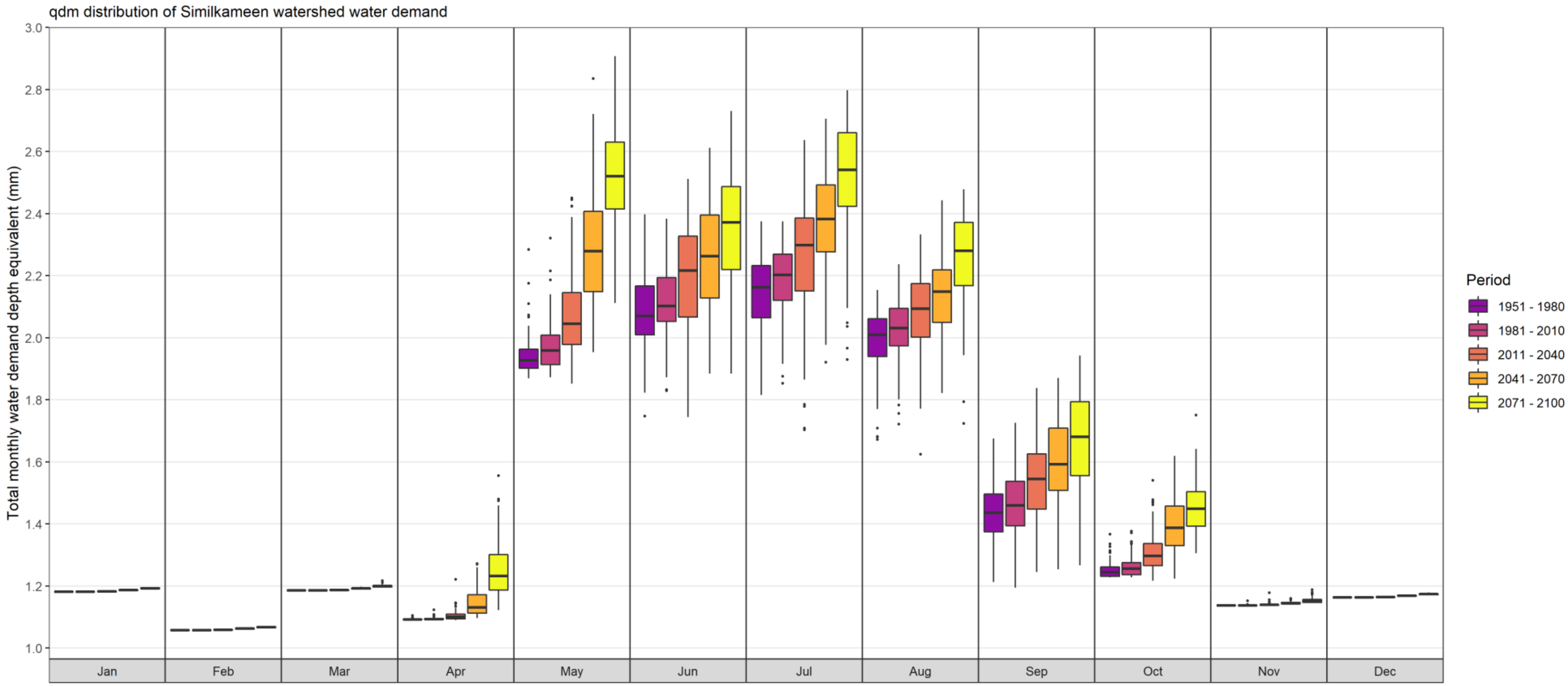

Figure 4-2 – Watershed total monthly depth equivalent demand for five modelling periods. All four qdm datasets are lumped per period and month.

Some variability is present between the four climate datasets but they all indicate an increase in total demand; for example, the mean depth equivalent demand in July during 1981-2010 is 2.19 mm, but this increases to 2.59 mm by July 2071-2100. Additionally, the demand season begins earlier and ends later in the future periods. Average April depth equivalent demands increase from 1.09 mm in 1981-2010 to 1.25 mm in 2071-2100, and average October demands increase from 1.26 mm to 1.45 mm, respectively. The increase in total demand is a result of population growth-driven demand and agricultural irrigation needs under future climate conditions. The increased demand is a result of a longer growing season and increased crop irrigation requirements due to warmer air temperatures predicted for the watershed into the future[17].

5 SUMMARY

Daily water demand estimates for each Similkameen River watershed sub-basin were generated for the 1945-2100 period. A summary of the work completed is as follows:

- Current Canadian water demand was derived from water use licences and outputs from the AWDM.
- Current United States water demand was derived from reported surface water withdrawals (USGS 2021) and DOE water rights.
- Future Canadian and United States domestic water use was increased to account for population growth.
- Future Canadian agricultural water demand was generated by the AWDM using four GCM outputs, and United States irrigation water demand was scaled according to the future increases in Canadian agricultural water demand (based on the AWDM output).

The results of the water demand modelling using the future climate ensemble datasets provided by NHC found the following:

- Peak monthly water demands increase by end-of-century as estimated by the AWDM using all four GCM outputs. Minimum monthly water demands (i.e., during the winter) remain constant.
- The length of the irrigation season increases as estimated by all four GCM outputs, with the season extending into April and October.

Finally, daily sub-basin water demand estimates were provided to NHC as *.rvt files, ready for application within the Similkameen River hydrologic model being developed using the Raven Hydrological Modelling Framework.

[17] The AWDM uses precipitation input from the GCMs to account for the effect of changes in precipitation on irrigation requirements.

6 CLOSURE

This technical memorandum provides documentation of the methodologies Associated used to develop the water demand datasets for NHC to implement in the Similkameen River watershed hydrologic model. We are available to answer any questions regarding the content in this memo. Please do not hesitate to call Drew Lejbak at (250) 826-9486 or Andras Szeitz at (250) 558-8283.

Prepared by:

Andras Szeitz, M.Sc., GIT
Environmental Scientist

Reviewed by:

Drew Lejbak, M.Sc.
Project Manager

Brian Guy, Ph.D, P.Geo.
Senior Geoscientist

AS