



Raven Model Deployment to Select Salmon Watersheds

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1 Introduction

The province of British Columbia (BC) is situated on Canada's west coast, spanning almost 12 degrees of latitude from north to south. Its geography is diverse, with several mountain ranges, and cooling Arctic and moderating Pacific influences, yielding 14 biogeoclimatic zones (Demarchi, 2011). Seven major rivers drain BC, the Fraser, Columbia, Peace, Skeena, Stikine, Liard and Yukon. Salmon are a cornerstone of BC's economy, ecology and culture, especially to its indigenous peoples. Five species of Pacific salmon, those that have their pelagic phase in the Pacific Ocean, are endemic to BC: Sockeye, Pink, Chinook, Coho and Chum (Pacific Salmon Foundation, 2022). In addition to the large Fraser and Columbia River basins, many small watersheds along the west coast of BC and Alaska also support salmon populations.

Several in-depth retrospective analyses of salmon habitat and survival, have been carried out by the Department of Fisheries and Oceans (DFO) in a handful of watersheds across BC, namely the Tahltan, Meziadin, Babine, Stuart-Takla, Quesnel, Chilko and Somass, and in Auke Lake, Alaska (Hyatt et al., 2015; Stiff et al., 2018b, 2018c, 2018a, 2017, 2015, 2013a, 2013b). In these eight watersheds, that cover a range of latitudes and biogeoclimatic zones (Figure 1), water temperature has been recorded and salmon populations have been counted over several decades. Additionally, observed streamflow records have been analyzed to quantify the hydrologic conditions that stress salmon. The work of Hyatt et al. and Stiff et al. demonstrates climate change has had an impact on salmon survival; temperatures are warmer; late-summer low-flows are lower, under such conditions, fewer salmon have survived migration to spawn (Stiff et al., 2018b).

Water temperatures in these watersheds will continue to increase and make conditions increasingly stressful for salmon during migration (Stiff et al., 2018b). Climate change is creating conditions that are further threatening salmon survival, not only in their migration period, but also throughout their freshwater life stages. The October 2022 drought left hundreds of salmon dead, unable to swim upstream (Narwhal, 2022). Recent extreme climate events, attributable to human-induced climate warming, such as the heat dome of the June 2021 (Philip et al., 2021) and the flood of November 2021 (Gillett et al., 2022) are harbingers of more frequent heat-waves, floods and droughts to come. Streamflow conditions in the Peace, Fraser and Columbia basins will generally have higher highs, lower lows and longer low-flow periods (Schnorbus et al., 2014; Schoeneberg and Schnorbus, 2020; Shrestha et al., 2019, 2017; Werner and Cannon, 2016). However, the several streams monitored and analyzed by the DFO have not been modelled and thus projected changes in the hydrology of these eight watersheds is unknown.

The response of salmon populations to shifting streamflow and thermal regimes varies with hydrologic regime type, such as rainfall, snowmelt or glacier melt fed streams (Bellmore et al., 2022). *“Changes in freshwater ecology due to natural and human forces are hypothesized as having three pathways of effects. These pathways include effects on the: (1) quantity and quality of spawning habitats; (2) productivity of nursery lakes for rearing; and/or (3) habitat conditions associated with migration of smolts / adults”* (Nelitz et al., 2011). Characterizing future streamflow conditions, in watersheds where salmon are monitored, with a physically based model that simulates key hydrologic processes, could aid in planning and management and thus improve the chance for survival of salmon populations.

2 Study Area

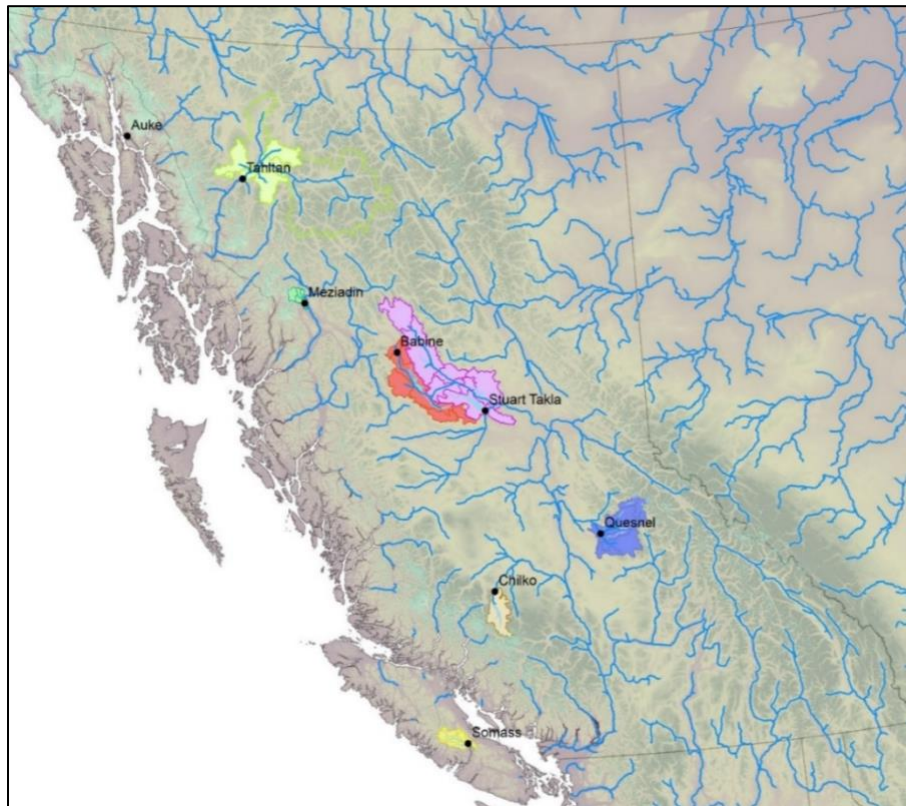


Figure 1. Location of Watersheds with Raven-UBCWM Implementations

The study area consists of eight watersheds spread across the full latitudinal expanse of BC (Figure 1; Table 1). The **Auke** watershed is the farthest North of all the BCSRIF basins, located near Juno, Alaska (Bethers et al., 2012; Juneau Watershed Partnership, 2009). It is 10.4 km² and has a lake with a surface area of 0.7 km². This coastal watershed ranges in elevation from 21 to 578 masl with a mean of 243 masl. Average annual precipitation is 1575 mm/year and evaporation is ~100 mm/year. The Auke is a hybrid nival-pluvial system with no glaciers. Observations of Auke Lake freezing and thawing have been made since 1961 (Taylor, 2008). This lake freezes over each winter, as early as November and as late as January, and melts out in late-April or early-May in combination with turnover (Taylor, 2008). Starting in 2000, midwinter breakup events, followed by refreezing were observed (Wing et al., 2006). The **Little Tahltan Weir** is in the western headwaters of the Stikine River at Telegraph Creek watershed (Figure 2). The Tahltan watershed upstream of the weir has an area of ~300 km². Tahltan Lake has a surface area of 5 km², a mean depth of 23 m, and max depth of 48 m (Hyatt et al., 2005; Stiff et al., 2013a). Due to a lack of streamflow records near the weir location, the Tahltan is modelled as part of the larger Stikine River at Telegraph Creek, which encompasses an area of 29000 km². To simulate flows in that reach, we use observed records from the Water Survey of Canada (WSC) to calibrate the Raven-UBCWM with a 200 m resolution over the greater Stikine watershed. The **Meziadin** watershed at the Outlet of Meziadin Lake drains 521 km² in the northwest of BC. The surface area of Meziadin Lake is 34 km² (Gilbert and Butler, 2004). It ranges from 246 to 2373 masl in elevation with a mean of 847 masl. WSC observations are not

available at the outlet of the lake, but do exist for Surprise Creek, WSC gauge 08DA005. The Surprise Creek sub-basin is 218 km² and has 18% glacier coverage by area.

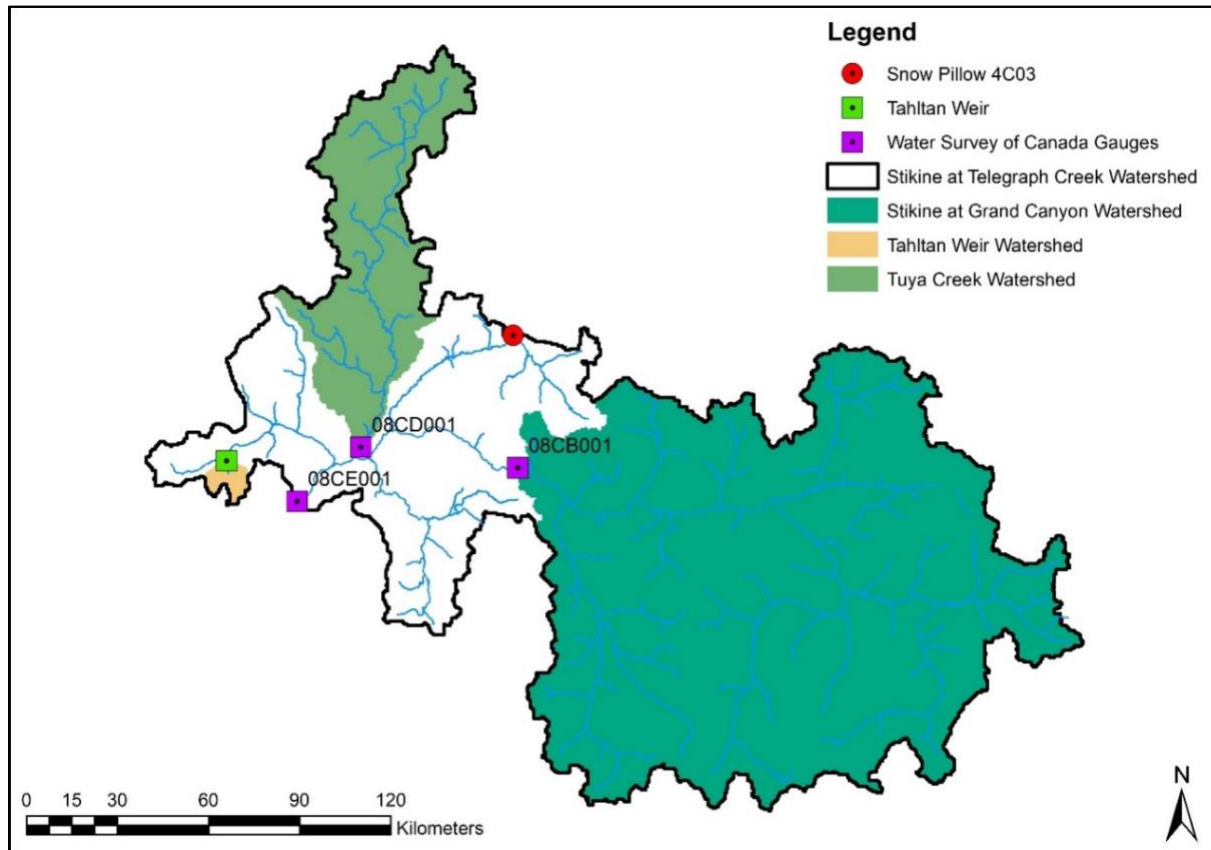


Figure 2. Example basin delineation for Stikine River at Telegraph Creek Watershed with Tahltan Watershed

The **Babine** watershed, with a total drainage area of 6479 km², is in the middle of the province. Elevation ranges from 648 masl to 2194 masl with an average of 1024 masl. Only a small portion of the watershed has glacier cover. Babine Lake is a long, narrow body of water located at an elevation of 711 m with a surface area of 479 km². The **Stuart-Takla** watershed is located in the middle of the province and has a drainage area of 14200 km². Elevations range from 682 m to 2100 m with an average of 986 m. The outlet of the watershed is delineated by the Water Survey of Canada (WSC) hydrometric gauge 08JE001, Stuart River Near Fort St. James. There are five major lakes in this system: listed from north to south they are Takla, Trembleur, Tezzeron, Pinchi and Stuart Lakes, with respective surface areas of 218.6 km², 116.2 km², 79.9 km², 54.9 km² and 358.8 km². These lakes comprise 6% of the basin by area. The **Quesnel** is a 5970 km² watershed ranging in elevation between 740 to 2612 masl, with an average of 1306 masl. The outlet of the basin is WSC gauge 08KH001, the Quesnel River at Likely. The watershed has four main lakes, Quesnel, Horsefly, Mitchell, and McKinley. Their surface areas are 252 km², 55 km², 21 km², and 7 km², respectively. The **Chilko** watershed is located high in the Coastal Range Mountains. Elevation ranges from a minimum of 1175 m to 3142 m with an average of 1809 m. There is one WSC gauge at the outlet

of the basin, Chilko River at the Outlet of Chilko Lake (08MA002). The total area drained is 2130 km², and glaciers make up 7% of the watershed area circa 2000. The **Somass** is a 1280 km² watershed ranging in elevation from 16 to 1775 masl, with an average of 586 masl. The basin outlet is defined by WSC gauge 08HB017, the Somass River near Alberni. Three lakes are located in the basin, Elsie Lake, Great Central Lake, and Sproat Lake. Their surface areas are 11 km², 51 km² and 38 km², respectively. Outflow from both Elsie Lake and Great Central Lake are regulated (Michalski and Schlag, 2014). The watershed is primarily rainfall-dominated with some seasonal snowpack at high elevations, but minimal glacier coverage. The hydrograph reflects a rapid response to rainfall and snowmelt events in combination with smoothing by water retained in lakes. The specific discharge is 7.4 mm/day, which is one of the highest in the province.

Table 1. Watershed Characteristics

Basin	Lat	Lon	Area (km ²)	Lake Area (km ²)	Glacier (%)	Mean Elev. (m)	Min Elev. (m)	Max Elev. (m)
Auke	58.408	-134.648	10.4	1	0	243	21	578
Tahltan	57.944	-131.551	300	5	0	1223	799	2041
Meziadin	56.148	-129.163	521	36	7	847	246	2373
Babine	54.792	-126.944	6479	479	0	1024	648	2194
Stuart	54.014	-125.307	14200	828	0	986	682	2100
Quesnel	52.482	-120.886	5970	335	1	1306	740	2612
Chilko	51.280	-124.051	2130	184	7	1809	1175	3142
Somass	49.374	-125.211	1280	100	1	586	16	1775

3 Methods

The University of British Columbia Watershed Model (UBCWm) is a hydrologic model suitable for modelling streamflow in the many snowmelt-dominated watersheds of BC (Morrison et al., 2002; Quick and Pipes, 1977). The UBCWm is emulated using the highly flexible Raven Hydrologic Modelling Framework. We deployed Raven-UBCWm with Raven v3.5, which allows lakes to be parameterized, or Raven v3.7, which allows Raven to be coupled to the Regional Glaciation Model (RGM), if glaciers are present. This work builds on other studies of climate change impacts in BC, including the fully-distributed version of Raven-UBCWm needed to couple to RGM (Tsuruta and Schnorbus, 2022, 2021) and the semi-distributed Variable Infiltration Capacity model with glaciers (VIC-GL) (Schoeneberg et al., 2021; Schoeneberg and Schnorbus, 2020). Both Raven-UBCWm and VIC-GL are parameterized with information from the detailed North America Land Change Monitoring System (NALCMS) vegetation library, which has 19 vegetation classes (Schnorbus, 2021), and are forced with ~5km a side, gridded meteorological dataset, PNWNAmet (Werner et al., 2019). We use air2Stream to predict daily averaged river water temperature as a function of air temperature and discharge (Toffolon and Piccolroaz, 2015).

3.1 Parameterization

Most basins were parameterized at a 500 m grid resolution (Table 2). Heavily glaciated basin, such as the Chilko were parameterized at 200 m grid resolution to better depict dynamic glacier change. The smallest basin, Auke, which is only 10 km², was parameterized at 100 metres. Each grid, or Hydrologic Response Unit (HRU), has a unique ID and elevation (Figure 3). Latitude and longitude are assigned with 5 decimal places of precision. Elevation is derived from the GMTED DEM, re-projected to BC Albers at 100-m resolution. Slope and Aspect are generated in ArcGIS using the aggregated GMTED DEM. Aspect values of zero are replaced with 90 degrees and all values are subtracted from 360 degrees to adjust to the Raven ready format. Reference Elevations are based on the VIC-GL GTOPO 30 DEM at 0.0625 decimal degree or 1/16° resolution. Basins were delineated such that sub-basins were defined where WSC observational records were available. This allowed the major features of the watershed, such as lakes, inlets to lakes or heavily glaciated areas to be explored.

Table 2. Watershed Model Characteristics

Basin	Res. (m)	No. HRUs	No. gl. HRUs	No. Subs	PADJ	Mean Elev. (m)	Min Elev. (m)	Max Elev. (m)
Auke	100	979	0	6	0.88	243	21	578
Tahlitan	500	27 391	117	8	1.00	1223	799	2041
Meziadin	500	2 713	200	5	1.00	847	246	2373
Babine	500	23 966	4	6	0.75	1024	648	2194
Stuart	500	51 991	25	7	0.85	986	682	2100
Quesnel	501	20 852	235	9	1.00	1306	740	2612
Chilko	200	48 456	3756	1	0.64	1809	1175	3142
Somass	500	4 774	4	5	1.10	586	16	1775

3.1.1 Vegetation and Land-use

Vegetation and land-use classes and their parameter values were borrowed from the deployment of Raven described in Tsuruta and Schnorbus (2022). This classification scheme was originally developed for the deployment of the Variable Infiltration Capacity with glacier modifications (VIC-GL) (Schnorbus, 2021). Land cover classification is based on the North America Land Cover dataset (Natural Resources Canada/The Canada Centre for Mapping and Earth Observation (NRCan/CCMEO) edition 2 produced as part of the North America Land Change Monitoring System (NALCMS). NALCMS is a 250-m resolution data set that divides North America into 19 land cover classes representing c. 2005 conditions. Schnorbus (2021) further subdivided the Temperate Needleleaf Forest class into four classes creating 22 classifications in total (Table 3). Parameters for each class, such as monthly Leaf Area Index, Roughness and Displacement were gathered into a vegetation library from a variety of sources.

The landcover in each basin is summarised in Table 4 and Figure 3. The highest percentage of land cover in most basins is occupied by the NTESP2, NTESP3 or NTESP4 classes, except for Chilko, which is classified as 30% BARREN. The Chilko and Meziadin are the most heavily glaciated, with 8% and 7% of their area classified as glacier. The remaining basins have 1% or less glacier coverage, or none in the case of the Auke.

Table 3. Vegetation classes (those in grey are not found in the BCSRIF basins).

Class	Description
NTESP1	Needleleaf Forest – temperate or sub-polar.1 – sub-alpine/sub-polar/open
NTESP2	Needleleaf Forest – temperate or sub-polar.2 – high-elevation
NTESP3	Needleleaf Forest – temperate or sub-polar.3 – mid-elevation
NTESP4	Needleleaf Forest – temperate or sub-polar.4 – coastal/humid/dense
NSPTA	Needleleaf Forest – sub-polar taiga
BETRSR	Broadleaf evergreen forest – tropical or sub-tropical
BDTRSR	Broadleaf deciduous forest – tropical or sub-tropical
BDTESP	Broadleaf deciduous forest – temperate or sub-polar
MF	Mixed forest
STRSR	Shrubland – tropical or sub-tropical
STESP	Shrubland – temperate or sub-polar
GTRSR	Grassland – tropical or sub-tropical
GTESP	Grassland – temperate or sub-polar
SLMSPP	Shrubland-lichen-moss – Sub-polar or polar
GLMSPP	Grassland-lichen-moss – Sub-polar or polar
BALMSPP	Barren-lichen-moss – Sub-polar or polar
WET	Wetland
CROP	Cropland
BARREN	Barren lands
URBAN	Urban and built-up
WATER	Water
GLACIER	Ice

Table 4. Percent of vegetation class in each basin.

Class	Auke	Babine	Chilko	Meziadin	Quesnel	Somass	Stuart	Tahltan
NTESP1	11	7	21	4	12	6	16	13
NTESP2	2	49	20	2	19	5	38	26
NTESP3	59	30	5	9	28	31	26	12
NTESP4	10	4	0	25	11	44	4	0
BDTESP	0	1	1	12	5	4	3	4
MF	0	0	0	8	0	2	0	14
STESP	18	3	11	5	10	5	6	11
GTESP	0	2	1	5	2	0	2	3
GLMSPP	0	0	1	0	0	0	0	5
BALMSPP	0	0	0	1	0	0	0	1
WET	0	0	0	0	0	0	0	1
BARREN	0	0	30	14	5	2	1	7
WATER	0	3	2	7	4	1	3	1
GLACIER	0.0	0.0	7.8	7.4	1.1	0.1	0.0	0.4

For the Raven-UBCWm each vegetation class requires twelve parameters (Table 5). Some of these values assigned to ensure they matched those available in Schnorbus (2021) and were, in many cases, converted to the units required by Raven (see Table A1, Appendix A). In our approach values for IMPERM, the fraction of the surface that is impermeable, were assigned a priori according to values for similar vegetation types in the Raven Tutorial materials for Alouette basin. MAX_LEAF_COND was set based on values provided in example materials in the Raven Manual and Tutorials. MAX_LEAF_COND of NTESP1, NTESP2, NTESP3 and NTESP4 was further refined such that values were the ratio of their MAX_HT versus MAX_HT of NTESP1 (16 m) times 5 mm s^{-1} . Confirmation of the validity of these values was given by Schulze (1994) and by comparing simulated (Figure 4) to LandFlux-Eval observed (Figure 5) evaporation. We adopted the Penman-Monteith evaporation method due to its physically based nature.

Average daily Actual Evapotranspiration (AET) simulated with Raven-UBCWm using the Penman-Monteith method compares well to the monthly LandFlux-EVAL dataset (Mueller et al., 2013) values in each basin (Figure 4 and Figure 5). The Chilko and Meziadin were exceptions. Low values in Chilko and sub-basins 1 and 2 in Meziadin are due to many HRUs of the class BARREN (Table 4 and Appendix A).

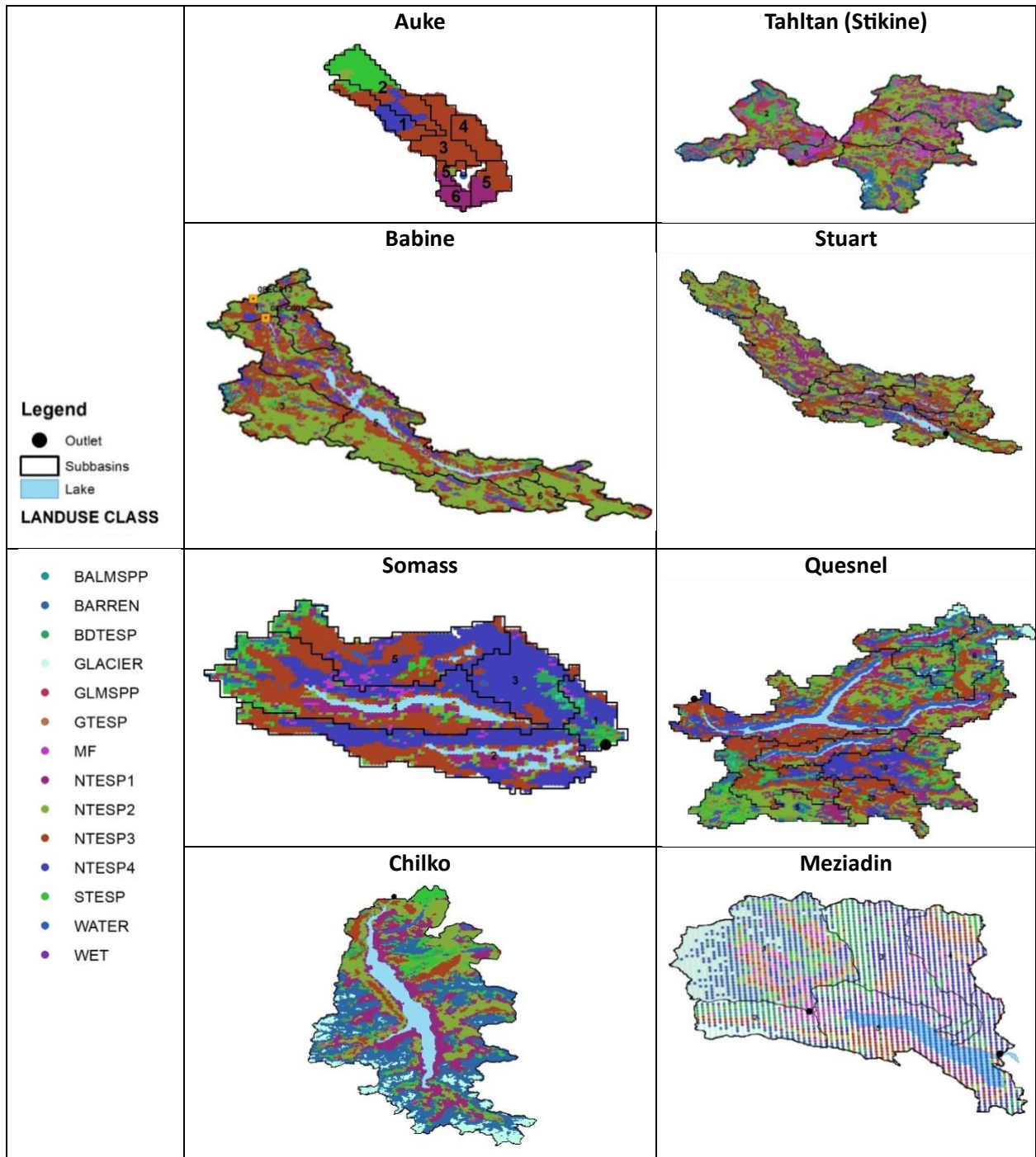


Figure 3. Hydrologic Response Units (HRUs) by basin.

Table 5. Vegetation and land use parameters

Name	Definition	Units	Source
<i>MAX_HT</i>	Maximum vegetation height	[m]	Table 5 Schnorbus (2021)
<i>MAX_LAI</i>	Maximum leaf area index	[m ² /m ³]	Max of Table 7 Schnorbus (2021)
<i>MAX_LEAF_COND</i>	Maximum leaf conductance	[mm/s]	Max of 5 from Raven 3.0.4 manual
<i>IMPERM</i>	Fraction of surface that is impermeable	[-]	Alouette Raven Tutorial
<i>FOREST_COV</i>	Fraction of land covered by vegetation canopy	[-]	1 if forested class
<i>Seasonal Canopy LAI</i>	A monthly correction factor that can be used to adjust leaf area indices as the seasons change, i.e., $LAI = LAI_{max} \cdot f$, where $f(t)$ is the monthly correction factor for time t .	[-]	Monthly LAI / MAX_LAI Table 7 Schnorbus (2021)
<i>UBC_ICEPT_FACTOR</i>	UBC Interception factor = $COTREE \cdot COCANY$. <i>COTREE</i> = Fraction of the band with tree cover, range [0-1], default [0]. <i>COCANY</i> = Density of tree cover (canopy), range [0-1], default [0]. Vegetation cover is homogenous across HRUs because small, so equal to <i>LAI</i> fraction.	[-]	Set to average of the Seasonal Canopy LAI (see above)
<i>FOREST_PET_CORR</i>	fraction of PET to apply to forest evapotranspiration	[-]	1 if veg
<i>LAKE_PET_CORR</i>	Fraction of PET to apply to open water evaporation	[-]	1 if water
<i>ROUGHNESS</i>	Roughness of ground surface	[m]	Ave. monthly values Table 11 Schnorbus (2021)
<i>SAI_HT_RATIO</i>	ratio of stem area index to height	[m ² /m ³]	Not sure where from
<i>ALBEDO</i>	Visible/near-infrared albedo of leaf	[-]	Ave. monthly values Table 9 Schnorbus (2021)

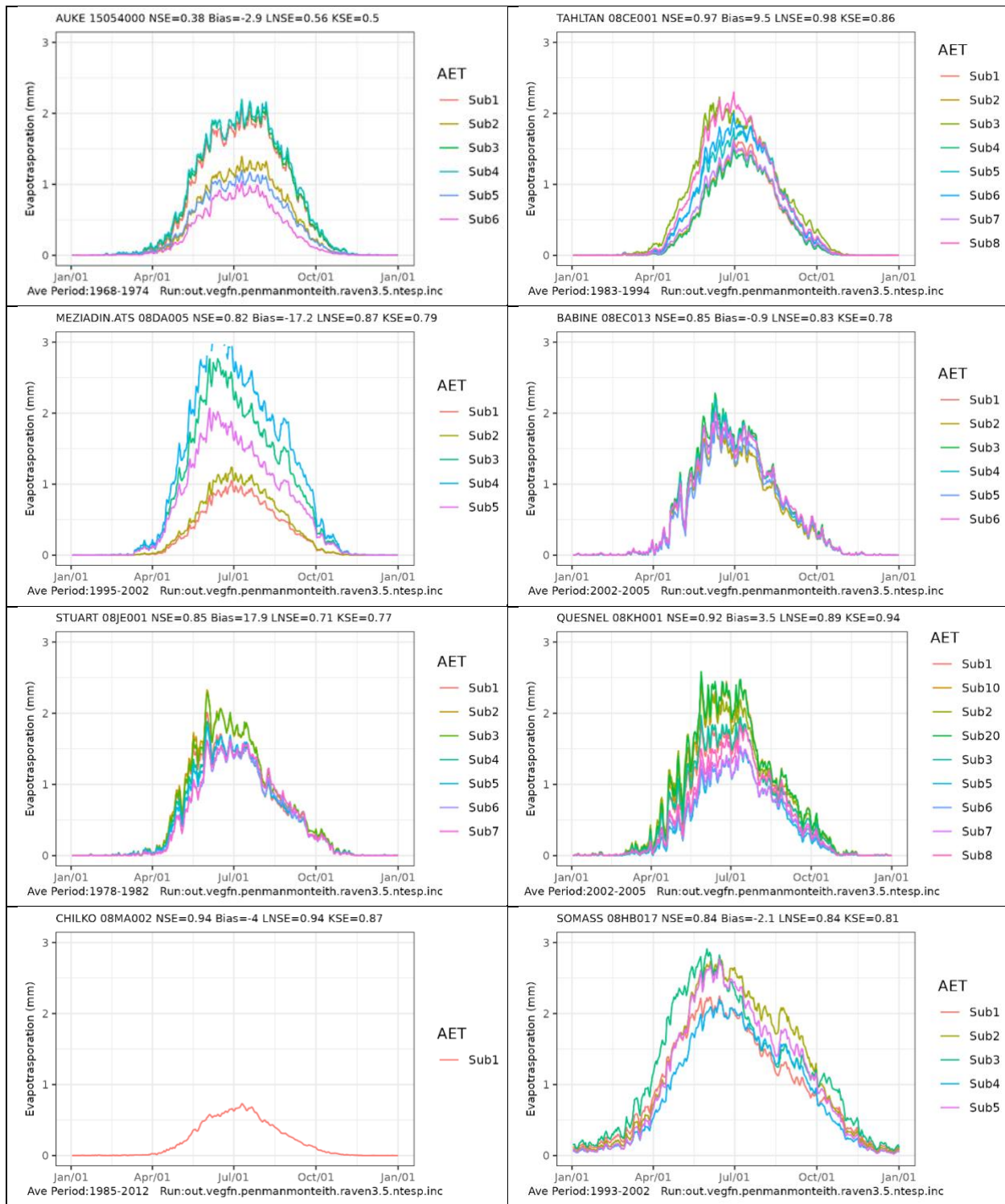


Figure 4. Average daily AET by subbasin in each watershed over calibration period

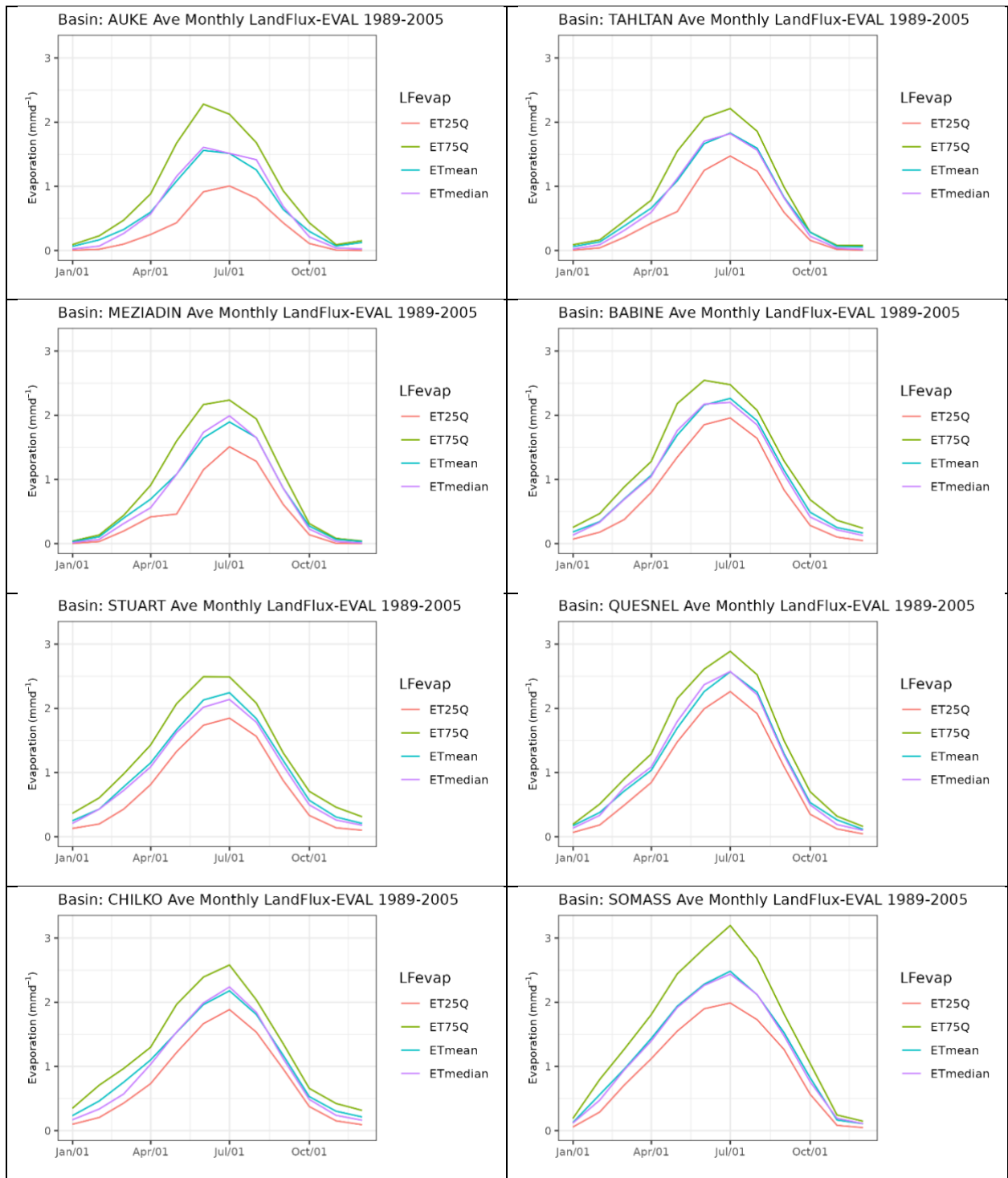


Figure 5. Monthly average "observed" evapotranspiration from the LandFlux-EVAL data product by sub-basin (1989-2005).

3.1.2 Channel Profile

Another fixed parameter was the Channel Profile. All basins were set with the default trapezoidal channel profile option. The routing algorithms employed are ROUTE_DIFFUSIVE_WAVE for channel routing (between sub-basins) and ROUTE_DUMP for catchment routing (HRU to sub-basin outlet).

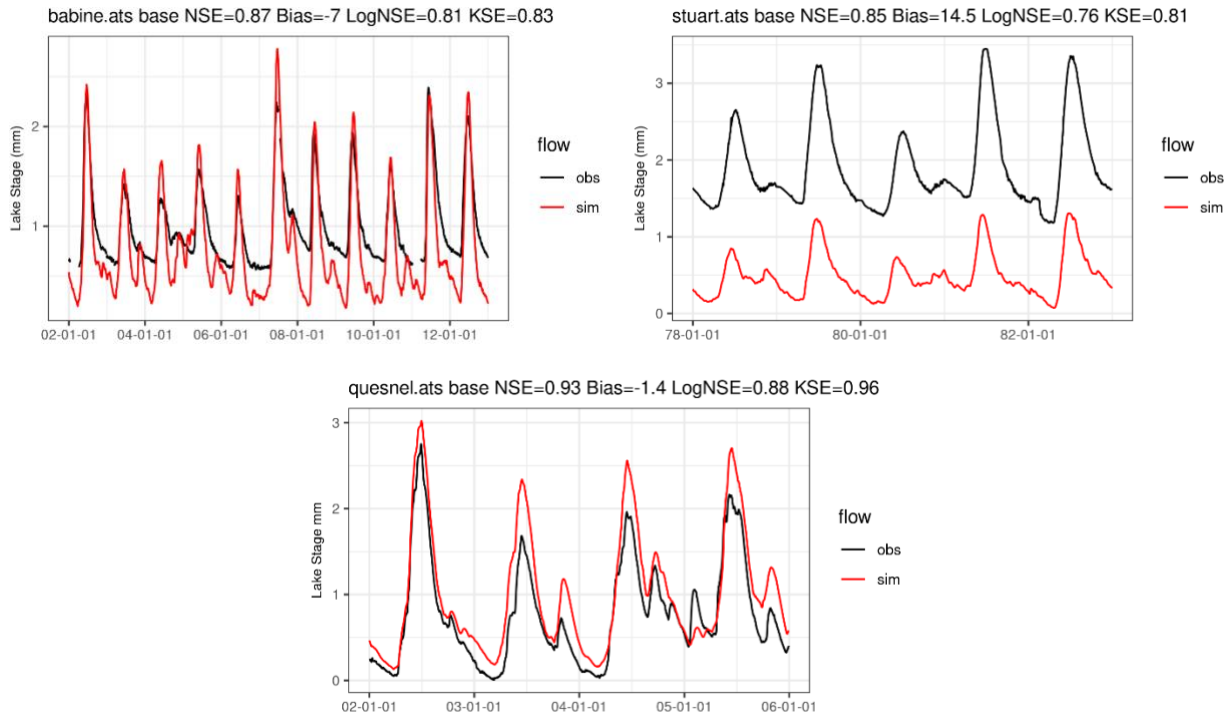


Figure 6. Daily Lake Stage for watersheds with lakes with observations (units are metres not mm).

3.1.3 Lake Parameterizations

All lakes are included as simple, natural lakes where stage-discharge curves are calculated by Raven. For natural lake routing configurations and equations, see Figure 4.1 in the RAVEN User's and Developer's Manual v3.0.4 (RAVEN development team, 2021). The crest width, max depth, weir discharge coefficient, and surface area of each lake is specified by the user (Table 6). Max depth and surface area were gathered from the literature. Both the crest width and weir coefficient parameters can be adjusted, but because these are multiplicative, the recommendation remains to fix the weir coefficient (usually at ~ 0.6) and calibrate the crest width (James Craig personal comm. June 21, 2022). In our case, crest width was adjusted manually in each basin until streamflow and or lake levels were favorable. Babine, Stuart, Quesnel and Chilko Lakes are some of the deepest in North America. In Raven v3.0.4, discharge curves are interpolated at a set of 100 points between elevations, which are too coarse for these massively deep lakes. Consequently, it was recommended max depth be set a bit below the lowest water level one might expect in the lake, so the volume corresponds to the active volume of the lake (James Craig personal comm. December 22, 2022). Max depth was set as actual max depth for smaller lakes and to no deeper than 35 m for large lakes (Table 6). In the Babine, Stuart, and Quesnel, where observations are

available, the model can simulate lake stage fluctuations, especially in the Quesnel (Figure 6). Lake stage is underestimated in the Stuart, while summer lows are not well simulated in the Babine.

Table 6. Lake Modelled Characteristics.

Basin	Reservoir	Sub Basin ID	HRU	Weir Coefficient	Crest Width (m)	Actual Max Depth (m)	Modelled Max Depth (m)	Lake Area (km ²)	References
Auke*	L1	4	766	0.6	0.6	34.4	34.4	0.7	Bethers et al. 2012
Tahlitan	None	-	-	-	-	48 m	-	4.92	Hyatt et al. 2005
Meziadin	None	-	-	-	-	133 m	-	34	Gilbert and Butler, 2004
Babine*	Bab	2	11396	0.6	15	235	34.4	158.8	Hume and MacLellan, 2000
Stuart	L1 Stuart	1	41575	0.6	58.8	96.6	50	365.8	www.lakepedia.com/Stuart
Quesnel	Quesnel	1	3194	0.6	30	511	34.4	266	wikipedia.org/wiki/Quesnel_Lake
	Horsefly	3	10866	0.6	15	193	34.4	59	wikipedia.org/wiki/Horsefly_Lake
	Mitchell	7	709	0.6	10	unknown	17.2	21.4	www.anglersatlas.com/place/145430/mitchell-lake
	McKinley	20	17964	0.6	2	unknown	4.4	5.2	www.anglersatlas.com/place/100758/mckinley-lake
Chilko	L1 Chilko	1	185540	0.6	15	366	35	184	www.lakepedia.com/Chilko
Somass	L5 Elsie	5	4980	0.6	3	20.7	8	6.2	Michalski and Schlag, 2014
	L4 GCL	4	7668	0.6	10	250	35	54.2	Michalski and Schlag, 2014
	L2 Sproat	2	11715	0.6	15	195	35	32	Michalski and Schlag, 2014

* Lake freezes in winter

3.2 Pre-Calibration

All models were initially run with default parameters to check for streamflow bias. Where absolute bias exceeded 10% precipitation adjustments (PADJ) from VIC-GL calibration over BC, if available, were used to adjust the precipitation inputs uniformly over the domain (Table 2). Both VIC-GL and Raven-UBCWM used the PNWNAmet gridded meteorological data for calibration. If not available, trial and error was used to establish suitable values. The process that determines the proportion of precipitation as snowfall is $0.5 + (TRANS+T)/DT$, where *TRANS* is the rain/snow transition temperature, *DT* is the temperature range over which mixed precipitation can occur, and *T* is the daily average temperature. Values for the rain-snow transition parameters were taken from values available for northwest North America (NWNNA) in the soil file developed for VIC-GL implementation.

3.3 Raven-UBCWM- Streamflow Calibration and Validation

Modelled streamflow was calibrated using an improved version of the non-dominated sorting genetic algorithm (NSGA-II) (Deb et al., 2002), an automatic evolutionary algorithm that solves the multiple

objective global optimization problem. NSGA-II converges to and provides a sample of the Pareto frontier, which is a set of all parameter vectors that produce non-dominated values of the objective function vector. Implementation of the NSGA-II algorithm was accomplished using the mco R package (Mersmann, 2014). NSGA-II was run using 30 generations and a population size of 60. Calibration was accomplished by adjusting the 14 parameters identified by Sgro (2016), although with the narrower parameter ranges suggested by Tsuruta (pers. Comm. 2020) (see Table 7). Calibration period and reference dataset differ by basin (Table 8).

Table 7. Model parameters and ranges used for calibration

Parameter	Description	MIN	MAX
POROSITY	Porosity of soil	0.4	0.5
A0TLZP	Temperature lapse with precipitation	0	7
A0TLXM	Lapse rate of maximum daily temperature	5	20
A0TLNM	Lapse rate of minimum daily temperature	0	10
POTEDL	Lapse rate of maximum temperature range	0	20
POALBMIN	Albedo of very deep and aged snowpack	0.1	0.3
POALBASE	value which the albedo initially decays to using POALBREC	0.6	0.7
POALBMLX	exp decay function chosen so albedo at of snowmelt season is roughly 0.4	1000	5000
POPERC	Groundwater percolation mm per day	15	25
POGRADU	Precip gradient factor for elevations greater than EOLHI	10	20
A0STAB	Precip gradient modification factor	0	1
V0FLAS	Flash flood threshold mm	20	80
PODZSH	Deep zone share percent	0.12	0.38
SNOW_SWI	Maximum liquid snow storage capacity as a fraction of snowpack SWE	0.04	0.07

Simulations were evaluated and final parameter sets chosen based on quantitative metrics and subjective evaluation of plots of daily average streamflow, daily streamflow, daily maximum SWE, daily soil moisture content by soil layer, and daily AET. Split-sample validation was performed using streamflow from a different period and with additional WSC observations, if available (Table 8). See Figure 7 and Figure 8 for daily average and daily streamflow over the calibration period.

After calibration all basins, except Auke, had NSE scores of 0.80 or greater, LNSE of 0.74 or greater and KSE of 0.75 or greater (Table 8). Thus, the Raven v3.5 - UBCWM model as parameterized is simulating streamflow well. Generally, performance during the validation period (Table 9) is comparable to that in the calibration period (Table 8) for all watersheds. All basins had biases within $\pm 10\%$, except Meziadin and Stuart. Surprise Creek, the calibration site for Meziadin, has a deficit of 19%, which is noticeable in the recession limb of the hydrograph. Issues with persistent snowpack are apparent in this basin. Further modifications to the parameterizations, especially pertaining to snow and glacier melt are needed. The Stuart-Takla is biased positively with an excess of 15%. Simulations exceed observations primarily in October through April (Figure 8). Precipitation in the Stuart-Takla was adjusted by 0.854, which improved performance greatly. However, due to the large size of the basin, it is possible that some regions require

further adjustments. Unfortunately, there are no WSC streamflow observations within the Stuart-Takla that could help to refine parameterizations across this large watershed.

The Auke basin is the furthest north and smallest at 10 km². It lies in a region with large annual precipitation depths. Approximately, one tenth of the watershed is taken up by the lake, which freezes in the winter (Juneau Watershed Partnership, 2009). The main snowmelt freshet from April through July is well captured by the model, however, many large intermittent events scattered in the months outside of this are not. This could be caused by smoothing of precipitation events in the PNWNAMet gridded dataset. It could also relate to lake effects, such as fill and spill, which are not well captured with the current parametrization.

Quesnel has additional WSC gauges that allowed validation across the basin. Although performance at the Outlet, 08HK001, is the best out of all the watersheds, there is a positive flow bias in the sub-basin above WSC gauge 08KH020 (McKinley Creek below the Outlet of McKinley Lake), which is part of the Horsefly River basin. VIC-GL PADJ values were different in Horsefly River basin than they were for Quesnel. Currently, no PADJ is made for the Quesnel.

For reference, Table 10 provides the final calibrated parameter values, including the three parameters adjusted during pre-calibration (Section 3.2).

Table 8. Calibration station, calibration period, selected run and performance metrics by basin

Basin	Station	Start	End	Spin-up	Selected	NSE	BIAS	LNSE	KSE
Auke	15054000	1962-08-01	1968-08-01	to 1965-10-01	28Mar22 r4	0.54	10	0.66	0.73
Tahlitan	08CE001	1980-01-01	1995-04-01	to 1983-01-01	28Mar22 r1	0.98	1	0.98	0.90
Meziadin	08DA005	2000-01-01	2012-12-31	2000 and 2001	Not calibrated	0.80	-19	0.88	0.75
Babine	08EC013	2000-01-01	2006-01-01	2000 and 2001	12Apr22 r3	0.84	-1	0.74	0.82
Stuart	08JE001	1973-01-01	1982-12-31	1973 to 1977	13May22 r1	0.85	14	0.76	0.81
Quesnel	08KH001	2000-01-01	2006-01-01	2000 and 2001	26Apr22 r58	0.93	-1	0.88	0.96
	08KH020	2000-01-01	2006-01-01	2000 and 2001	26Apr22 r58	0.46	45.2	0.41	0.49
	08KH010	2000-01-01	2006-01-01	2000 and 2001	26Apr22 r58	0.84	7.6	0.75	0.89
Chilko	08MA002	2000-01-01	2007-01-01	2000 and 2001	Not calibrated	0.94	-10	0.92	0.87
Somass	08HB017	1991-01-01	2002-12-31	1991 and 1992	28May22 r3	0.85	-2	0.82	0.82

The water balance components of each watershed are given in Table 11. Precipitation is an order of magnitude greater in the Meziadin and Somass than all other basins, which is predominantly snowfall in the Meziadin and rainfall in the Somass. Evaporation is lowest in the Chilko (88 mm/year) and highest in the Somass (312 mm). R/P values are greater than 0.5 in the glaciated basins and in the highly productive Somass with an R/P of 0.86 (specific discharge Q of 7.4 mm/day).

Table 9. Validation station, validation period and performance metrics by basin

Basin	Station	Start	End	Spin-up	Selected	NSE	BIAS	LNSE	KSE
Auke	15054000	1965-08-01	1975-09-01	to 1968-08-01	28Mar22 r4	0.52	9	0.66	0.67
Tahltan	08CE001	1980-01-01	1995-04-01	to 1983-01-01	28Mar22 r1	0.97	9	0.98	0.88
Meziadin	08DA005	1990-01-01	2002-12-31	1990 and 1991	Not calibrated	0.81	-20	0.85	0.76
Babine	08EC013	2003-01-01	2012-12-31	2003 and 2004	12Apr22 r3	0.87	-8	0.81	0.83
Stuart	08JE001	1983-01-01	1995-12-31	1983 to 1987	13May22 r1	0.82	19	0.70	0.78
Quesnel	08KH001	2004-01-01	2011-12-31	2004 and 2005	26Apr22 r58	0.94	1	0.85	0.95
	08KH020	2004-01-01	2011-12-31	2004 and 2005	26Apr22 r58	0.59	44	0.40	0.52
	08KH019	2004-01-01	2011-12-31	2004 and 2005	26Apr22 r58	-1.07	138	-0.38	-0.61
Chilko	08MA002	2005-01-01	2011-12-31	2005 and 2006	Not calibrated	0.95	-6	0.86	0.93
Somass	08HB010	1959-01-01	1978-12-31	1959 and 1961	28May22 r3	0.63	-2	0.51	0.65
	08HB017	1959-01-01	1978-12-31	1959 and 1961	28May22 r3	0.81	-1	0.76	0.77

Table 10. Calibrated Parameter Values.

Parameter	Auke	Tahltan	Meziadin	Babine	Stuart	Quesnel	Chilko	Somass
<i>PADJ</i>	1.00	0.00	1.00	0.75	0.75	1.00	0.64	1.10
<i>TRANS</i>	1.00	1.00	1.95	2.30	2.30	1.00	1.00	-0.50
<i>DT</i>	2.00	2.00	11.90	13.10	12.99	2.00	2.00	2.00
<i>POROSITY*</i>	0.47	0.41	0.50	0.49	0.40	0.46	0.41	0.42
<i>AOTLZP</i>	0.03	6.99	7.40	6.89	4.81	5.54	6.33	5.62
<i>AOTLXM</i>	14.33	11.91	6.49	19.89	5.01	15.26	10.07	13.99
<i>AOTLNM</i>	0.34	0.89	0.34	9.93	0.30	1.96	1.61	2.43
<i>POTEDL</i>	18.98	13.44	4.52	19.99	19.96	18.36	10.96	19.60
<i>POALBMIN</i>	0.26	0.29	0.30	0.12	0.13	0.27	0.21	0.14
<i>POALBASE</i>	0.62	0.70	0.64	0.66	0.60	0.62	0.68	0.61
<i>POALBMLX</i>	1017.50	4990.92	3982.20	1033.97	1014.42	2986.00	3364.79	1067.49
<i>POPERC</i>	15.00	22.10	15.02	17.46	17.02	21.14	24.84	15.00
<i>POGRADU</i>	10.15	14.09	11.93	20.00	19.91	16.64	19.71	19.53
<i>AOSTAB</i>	0.99	0.26	0.84	0.00	0.04	0.32	0.00	0.00
<i>VOFLAS*</i>	20.03	42.50	30.00	33.24	50.61	52.14	43.00	53.20
<i>PODZSH*</i>	0.12	0.38	0.37	0.33	0.12	0.16	0.38	0.37
<i>SNOW_SWI</i>	0.04	0.07	0.05	0.07	0.05	0.07	0.07	0.05

Table 11. Water Balance of each watershed

Basin	Rainfall (mm/year)	Snowfall (mm/year)	Precipitation (mm/year)	Evaporation (mm/year)	Runoff (mm/year)	Runoff/Prec (-)	Specific Q (mm/day)
Auke	265	169	434	175	228	0.53	0.6
Tahltan/Stikine	311	378	689	180	-	-	-
Meziadin	560	784	1344	175	1012	0.75	2.8
Babine	219	216	434	175	228	0.53	0.6
Stuart	237	261	498	171	282	0.57	0.8
Quesnel	532	400	932	226	628	0.67	1.7
Chilko	196	427	623	88	537	0.86	1.5
Somass	2887	582	3141	312	2702	0.86	7.4

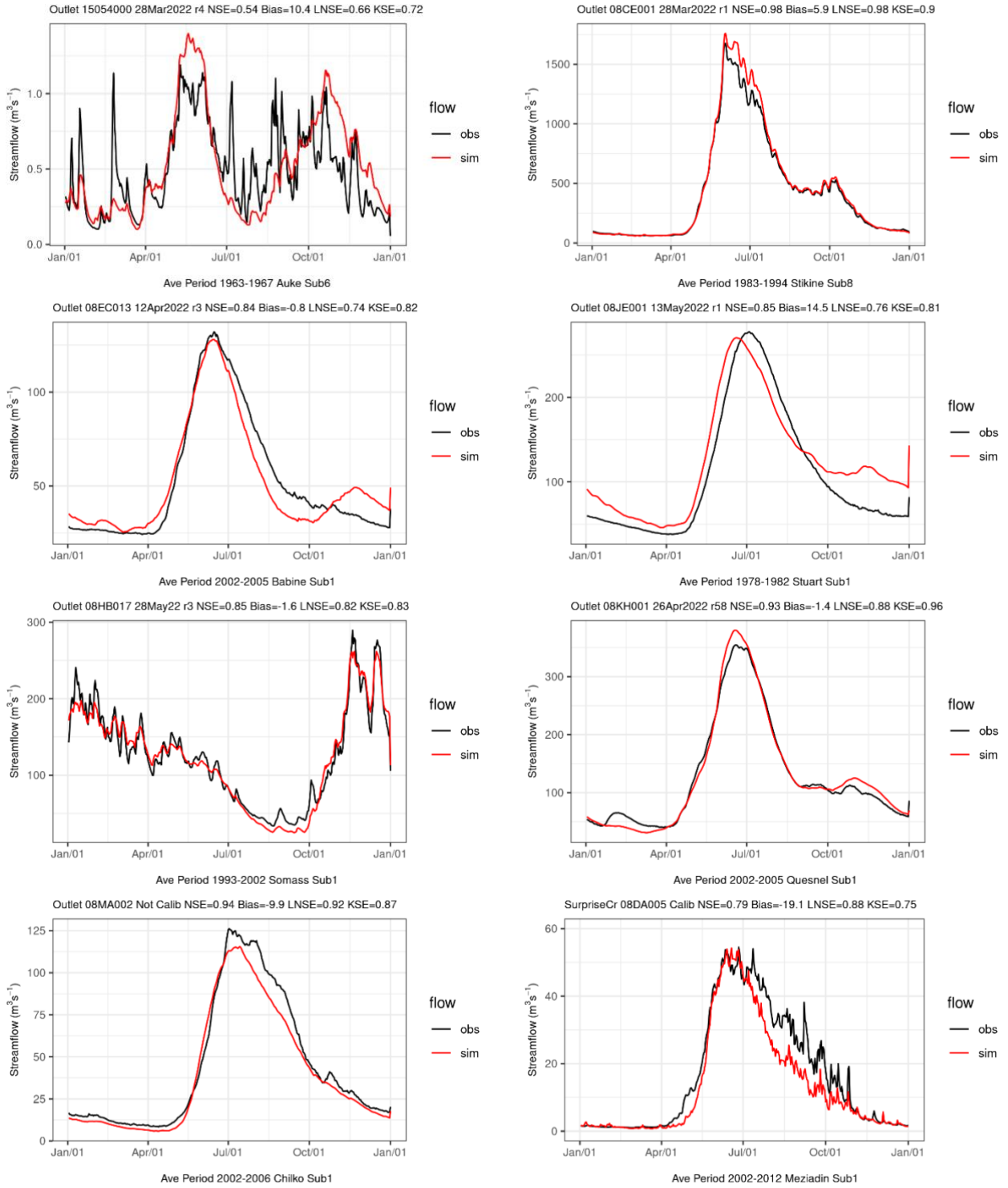


Figure 7. Average daily streamflow for calibration period all eight BCSRIF basins

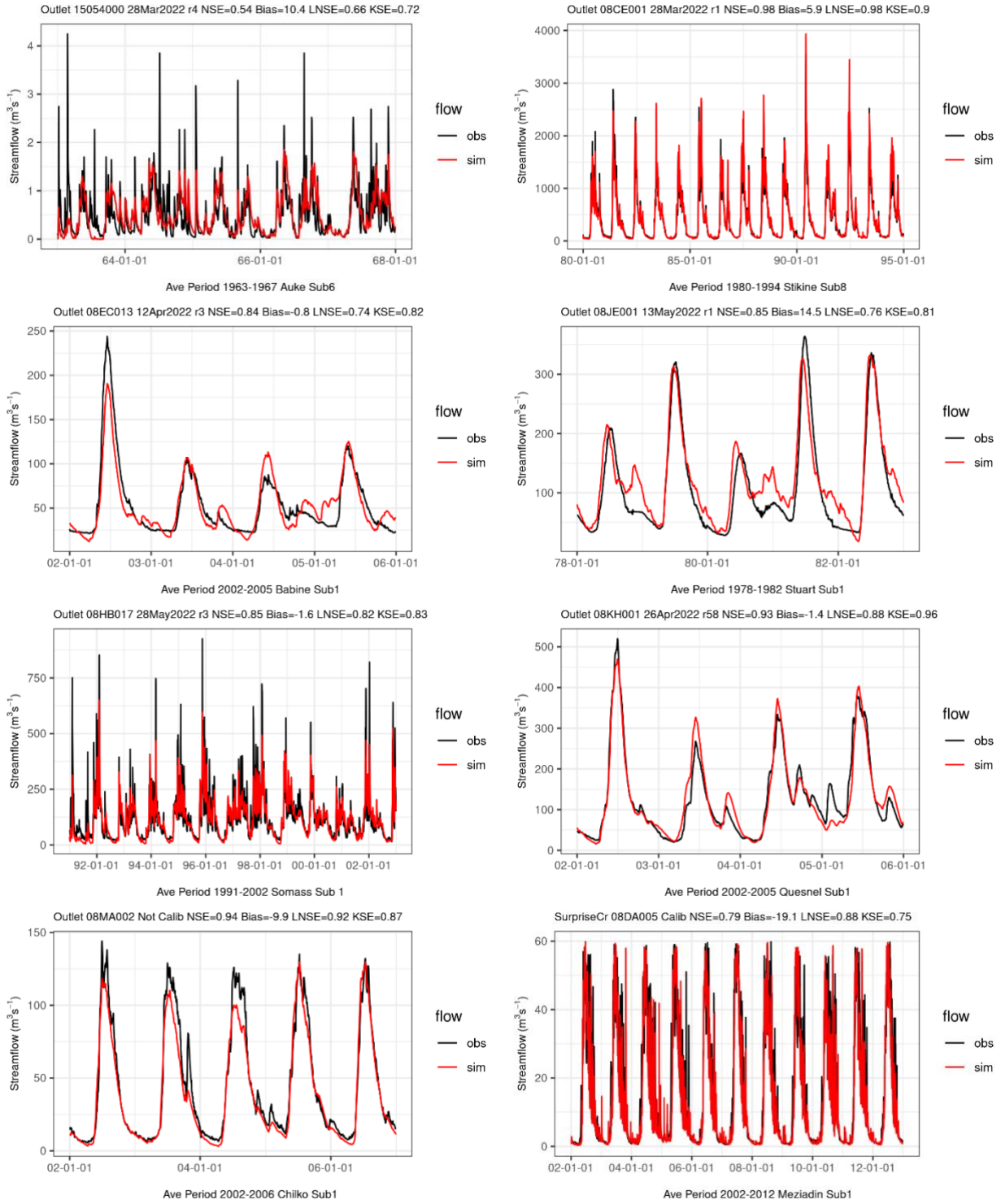


Figure 8. Daily streamflow for calibration period all eight BCSRIF basins

3.4 Raven-RGM Coupling

Coupling of Raven v3.7 to the Regional Glaciation Model (RGM) is achieved by utilising the ‘Custom Output’, ‘Call External Script’, and ‘Read Live File’ features of the Raven model (Figure 9).

On September 29th of each year, Raven is paused and outputs of glacier ice state and snow state by HRU (Raven Custom Output in Figure X) are used to estimate annual glacier mass balance (Equation 1).

$$M(t2, t1) = (swet2 - sweti) + (icet2 - iceti) \quad (1)$$

Using the model wrapper, via `CallExternalScript`, the mass balance is converted into a raster (pre-processing step in Figure 9). The mass balance raster, glacier surface DEM from the previous time step and the static bed DEM are then used to drive the RGM. The updated surface DEM produced by the RGM is used to calculate which HRUs have become glaciated and which ones are no longer glaciated (post-processing step in Figure 9). These lists of HRUs are used to create the read live file that tells RAVEN which HRUs have to be converted. Where glaciers are lost land use and vegetation type are changed to BARREN, and the HRU type is changed to ROCK. Where glaciers are gained the land use, vegetation type, and HRU type are changed to GLACIER.

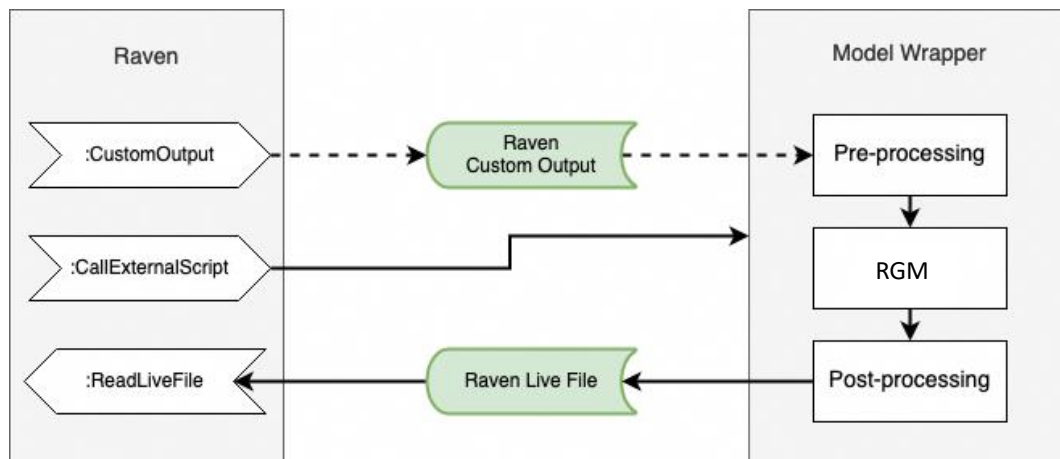


Figure 9. Schematic of Raven to RGM coupling procedure.

3.5 Glacier Initialization

The coupled Raven-RGM model requires three raster layers as input: (1) a bed DEM, (2) a surface DEM, and (3) and a glacier mass balance. The bed DEM is the underlying rock layer. The surface DEM is the land surface including that of glaciers. Thus, surface DEM – bed DEM equals the glacier thickness and provides the glacier mask. The RGM uses the bed DEM and surface DEM, along with the supplied mass balance, to model the dynamic evolution of the glacier and provide an updated surface DEM that reflects mass balance changes. However, the RGM requires two things to be true: (1) the bed DEM is less than surface DEM and (2) the difference between the bed DEM and surface DEM is greater than or equal to 1 m. This can be challenging because the bed DEM and surface DEM can have different provenance and coordinate systems. We developed a process to create a bed DEM that is a hybrid of the bed and surface

DEMs, which ensures the surface DEM is greater or equal to the bed DEM, where differences are greater than 1 m.

To calibrate over 1985 to 2005, models were initialized in 1981, with a hybrid bed DEM, surface DEM and initial glacier mask of circa 1985 conditions, created with the Terrain Resource Information Management (TRIM) surface DEM and a bed DEM (Clarke et al., 2015) (Figure 10). See Table 12 for full data descriptions. The change in surface area over 1985 to 2005 in the model vs. the change between UNBC’s 1985 and 2005 glacier surface areas (Figure 6; Provided by B. Menounos, UNBC) was used as an additional objective function in calibration (see Appendix B). For climate projections, the model needed to be initialized earlier than 1981 and given more spin up time to equilibrate the glacier with the climate of the GCM. The climate of the GCM is out of sync with the historical climate and likely out of phase with natural climate variability acting on glaciers. Therefore, initial glacier masks for projections were created by subtracting the 1945 Climate Research Unit (CRU) DEM based model run (Clarke et al., 2015) from by the Bed DEM (Clarke et al., 2015) (Figure 11). More details these data products are provided in Table 12.

One caveat to the initialization of the models for projections was that the glacier surface estimated with the 1945 CRU dataset was not always larger in area than that from the 1985 UNBC. This was true for the Quesnel and Chilko watersheds (1945 CRU area < 1985 TRIM area, see Table 13 and Table 14). One would expect glaciers to be larger, covering more area and having more mass, earlier in the record, when temperatures were cooler, as we saw in Surprise Creek (1945 CRU area > 1985 TRIM area, see Table 15 and Figure 11). Because glacier areas were larger with 1985 TRIM surface DEM than those from 1945 CRU surface DEM, in the Chilko and Quesnel basins, the 1985 TRIM surface DEM was used to initialize glaciers in these basins.

Table 12. Data products used for glacier initialization.

Descriptor	File name	Provenance	Coord.
Bed DEM 1985	bed_dem_lcc_200m_TRIM_merge.tif	Clark et al. 2015	NAD83
Surface DEM 1985	TRIM 1:20,000 (25 m)	https://www2.gov.bc.ca/	NAD83
Glacier Area 1985	glacinvent_1985_poly_final_ID.shp	B. Menounos, UNBC	NAD83
Glacier Area 2005	glacinvent_2005_poly_final.shp	B. Menounos, UNBC	NAD83
Bed DEM 1945	bed_dem_bc_lcc_v2.tif	Clark et al. 2015	LCC
Surface DEM 1945	surf_1945_cru_lcc.tif	Clark et al. 2015	LCC
Surface DEM 1945	surf_1945_cru_epsg3005.tif (100 m)	Reprojected from Clark	NAD83

Table 13. Glacier Statistics on Quesnel Watershed

Statistic	Value
Watershed area	5970 km ² (1% glacier coverage 1985)
No. of HRUs	20853
Resolution	500 m x 500 m
Raven initialized glacier area 1945	55.00 km ² (220 glacier HRUs x 0.25 km ²)
Raven initialized glacier area 1981	70.75 km ² (283 glacier HRUs x 0.25 km ²)
Glacier area 1945 CRU	55.00 km ² (0.009%)
Glacier area 1985 UNBC	73.3 km ² (1.2%)
Glacier area 2005 UNBC	61.7 km ² (1.0%)
Glacier area lost 1945 to 2005 UNBC	+6.7 km ²
Glacier area lost 1985 to 2005 UNBC	-11.7 km ²

Table 14. Glacier Statistics on Chilko Watershed

Statistic	Value
Watershed area	2130 km ² (7% glacier coverage 1985)
No. of HRUs	48456
Resolution	200 m x 200 m
Raven initialized glacier area 1945	104.56 km ² (2614 glacier HRUs x 0.04 km ²)
Raven initialized glacier area 1981	172.56 km ² (4314 glacier HRUs x 0.04 km ²)
Glacier area 1945 CRU	128.64 km ² (6.0%)
Glacier area 1985 UNBC	155.5 km ² (7.3%)
Glacier area 2005 UNBC	134.5 km ² (6.3%)
Glacier area lost 1945 to 2005 UNBC	+5.86 km ²
Glacier area lost 1985 to 2005 UNBC	-21 km ²

Table 15. Glacier Statistics for Surprise Creek

Statistic	Value
Watershed area	218 km ² (18.9% glacier coverage 1985)
No. of HRUs	888
Resolution	500 m x 500 m
Raven initialized glacier area 1945	50.25 km ² (201 glacier HRUs x 0.25 km ²)
Raven initialized glacier area 1981	41.75 km ² (167 glacier HRUs x 0.25 km ²)
Glacier area 1945 CRU	50.25 km ² (23.0%)
Glacier area 1985 UNBC	41.2 km ² (18.9%)
Glacier area 2005 UNBC	36.1 km ² (16.6%)
Glacier area lost 1945 to 2005 UNBC	-14.15 km ²
Glacier area lost 1985 to 2005 UNBC	-5.1 km ²

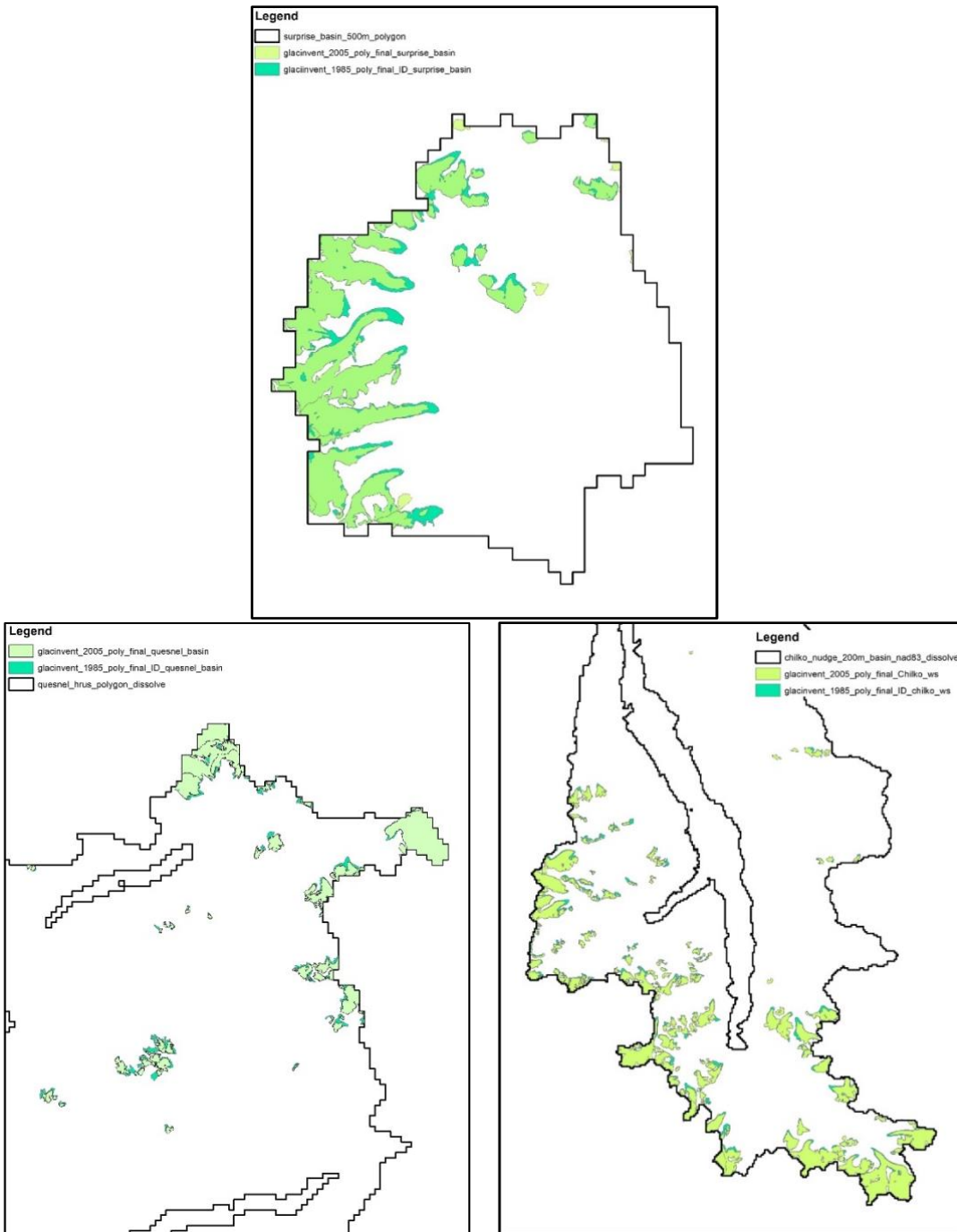


Figure 10. Glacier area circa 1985 and 2005.

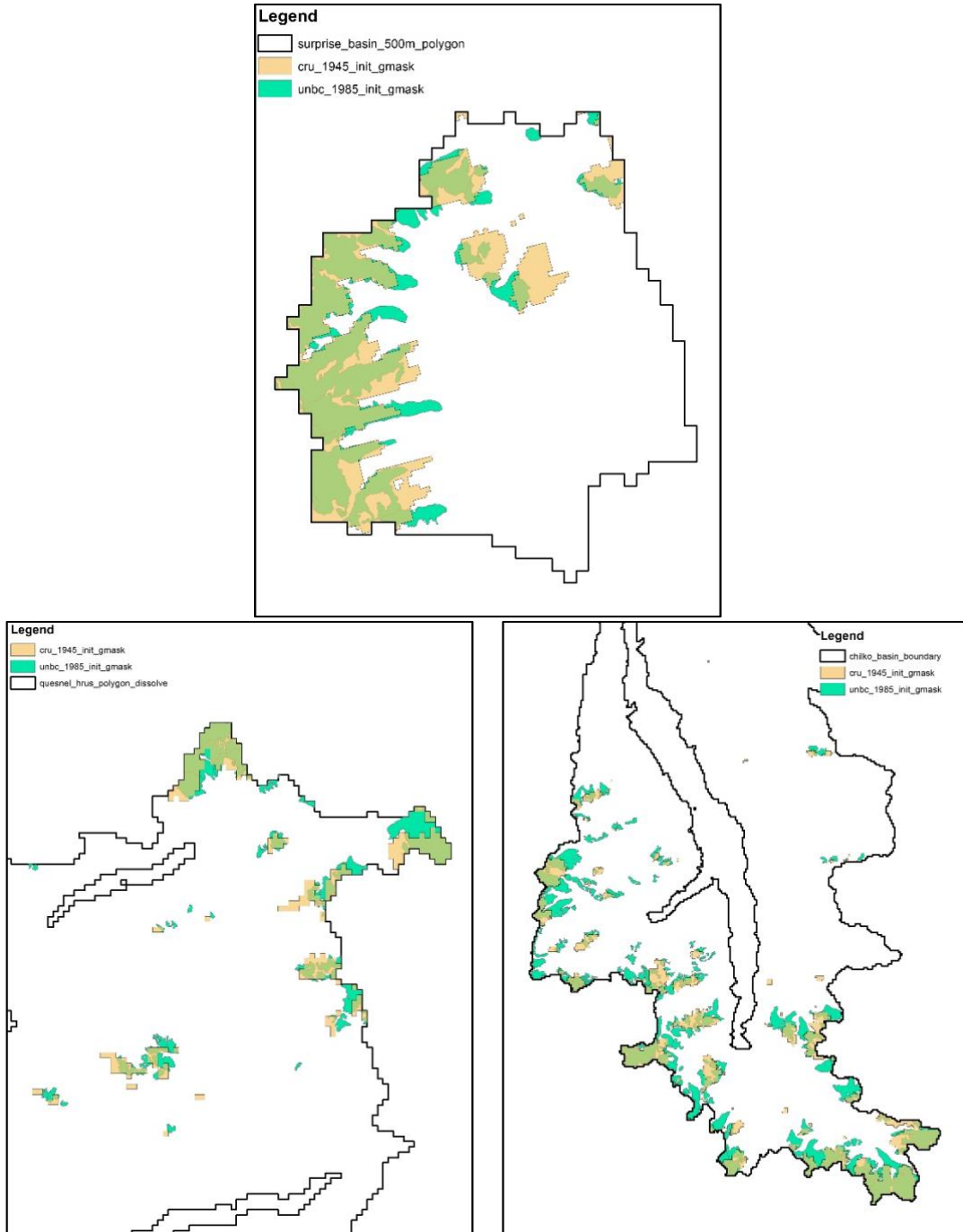


Figure 11, Initial glacier masks estimated for 1945..

3.6 Water Temperature Modelling

Water temperature modelling was conducted with the air2water or air2stream models depending on whether water temperature was monitored in the lake or in a stream (Table 16). Air2water is a lake surface temperature model requiring only air temperature. Air2stream is stream water temperature model that requires air temperature and streamflow.

Table 16. Locations, calibration and validation periods, and model used to simulate stream temperature by watershed.

Basin	Station	Lake Mean depth [m]	Lake Max depth [m]	Calibration period	Validation period	Model
Auke Watershed	Auke Creek Hatchery weir at the lower end of the stream	19	31	1980-1999	2000-2012	Air2water
Little Tahltan Weir	Outlet of Tahltan Lake	23	48	1999-2008	2009-2012	Air2water
Meziadin Watershed	Meziadin fishway (located <5km from the lake outlet)	66	134	1999-2007	2008-2012	Air2water
Quesnel watershed	Quesnel at Likely	157	506	2000-2010	2011-2012	Air2water
	Lower horsefly river above Quesnel Lake	66	190	1995-2004	2005-2012	Air2water
Babine Watershed	Babine fence at the outlet of Nilkitkwa Lake	4	19	2003-2012	–	Air2water
Somass watershed	Sproat River at the outlet of Sproat Lake	66	195	1996-2008	–	Air2water
	Stamp River at the outlet of Great Central Lake	212	–	2005-2008	–	Air2water
Stuart-Takla	Stuart River at Fort St. James	–	–	–	–	Air2water
Chilko-Chilkotin watershed	Chilko River at DFO stock assessment site	–	–	2000-2013	–	Air2water
	Chilcotin River below Big Creek and near Alexis Creek	–	–	2011-2013	–	Air2steam

Air2water v2.0 was downloaded from <https://github.com/spicolroaz/air2water>. This model relies on air temperature only to estimate lake surface water temperature. The air2water model is derived from the volume-integrated heat balance equation applied to upper volume of the lake that is affected by heat exchange with the atmosphere. The model is described by the following ordinary differential equation:

$$\frac{dT_w}{dt} = \frac{1}{\delta} \{a_1 + a_2 T_a - a_3 T_w + a_5 \cos \left[2\pi \left(\frac{t}{t_y} - a_6 \right) \right] \} \quad (2)$$

$$\text{with: } \begin{cases} \delta = \exp \left(-\frac{T_w - T_h}{a_4} \right) & \text{for } T_w \geq T_h \\ \delta = \exp \left(-\frac{T_h - T_w}{a_7} \right) + \exp \left(-\frac{T_w}{a_8} \right) & \text{for } T_w < T_h \end{cases} \quad (3)$$

where t is time, T_w and T_a are water temperature and air temperature in °C, δ is a dimensionless parameter which represents the ratio between the average depth of the surface layer and that of a reference layer, t_y is the duration of a year in the units of time considered in the analysis (here days), T_h

is the reference value of the deep-water temperature, a_1 - a_8 are the model parameters. Equation (2) represents the combined effect of meteorological variables particularly the coefficient \hat{a}_5 integrates the seasonal variability of external forcing variables other than air temperature. It is associated with the amplitude of the annual variations of the solar radiation. Equation (3) emulates the progressive thinning of the surface water volume affected by the heat budget when the lake is stratified (first formula) and when the lake is inversely stratified (second formula).

Two model simplifications are available. A 6-parameter simplified version of the model assumes that $\delta = 1$ when the lake is inversely stratified. Under the same assumption, the 4-parameter simplified version of the model does not include the external sinusoidal forcing (i.e., $a_i = 0$). This version is appropriate in case the annual cycle of air temperature and/or water temperature are approximately sinusoidal. Model parameters should range within physically plausible values that were estimated based on the mean depth of the lake and as recommended in Piccoloroaz (2016). Here, we test the three available versions of the model. The model is calibrated using the Particle Swarm Optimization (Kennedy and Eberhart, 1995). The Root Mean Square Error (RMSE) between observed and simulated water temperature is used as objective function.

Table 17. RMSE of each version of the air2water model during calibration and validation periods.

Site	Model version	4-param (°C)	6-param (°C)	8-param (°C)
Auke Creek	Cal	1.03	0.91	0.91
	Val	1.11	0.99	1.00
Tahltan Lake	Cal	1.55	1.51	1.49
	Val	1.61	1.73	1.73
Lower Horsefly Lake	Cal	1.24	1.23	1.21
	Val	1.27	1.25	1.23
Quesnel Lake	Cal	1.35	1.28	1.26
	Val	1.27	1.12	1.06
Meziadin Lake	Cal	1.48	1.47	1.47
	Val	1.64	1.70	1.69
Babine Lake	Cal	1.18	1.16	1.16
Sproat Lake	Cal	0.82	0.80	0.80
Great Central Lake	Cal	1.01	0.95	0.95
Stuart Lake	Cal	1.04	0.93	0.93
Chilko Lake	Cal	1.07	1.07	1.07

The model was calibrated using the three available versions then validated for an independent period. In all cases, the full version of air2water (i.e., model with eight parameters) was retained as is it has higher performance than the simplified versions (Table 17). Indeed, the 8-parameter version of the model is more appropriate to the study sites given the presence of ice that affects the seasonal lake stratification modelled by Eq3.

Table 18 presents the performance of the air2water model during calibration and validation periods. The model has a good performance with RMSE between 0.91°C (Auke) and 1.49°C (Tahltan) during calibration

period and between 1°C (Auke) and 1.73°C (Tahltan) during validation. The timeseries bias and the summer bias is less than 1°C during calibration and validation periods for all sites. Because water temperature data for the Meziadin watershed are only available for July and August, bias is omitted from Table 18 and timeseries are not presented for this basin. Observed and simulated water temperature data are depicted in Figure 12 for the validation periods. Overall, the model simulates well water temperature seasonality.

Table 18. Performance of models adopted at each site.

Site	RMSE (°C)		Bias (°C)		Summer Bias (°C)	
	Cal	Val	Cal	Val	Cal	Val
Auke Creek	0.91	1.00	0.18	0.42	0.07	0.58
Tahltan Lake	1.49	1.73	0.54	1.11	0.05	0.22
Lower Horsefly River	1.21	1.23	2.23	1.19	0.44	0.74
Quesnel Lake	1.26	1.06	3.75	2.72	-0.03	-0.44
Meziadin	1.47	1.69	–	–	0.12	-0.83
Babine	1.16	–	0.18	–	-0.10	–
Sproat Lake	0.80	–	0.00	–	-0.11	–
Great Central Lake	0.95	–	-0.00	–	-0.25	–
Stamp Falls	0.77	–	-0.01	–	0.00	–
Stuart Lake	0.93	–	0.00	–	0.01	–
Chilko Lake	1.07	–	0.13	–	0.37	–

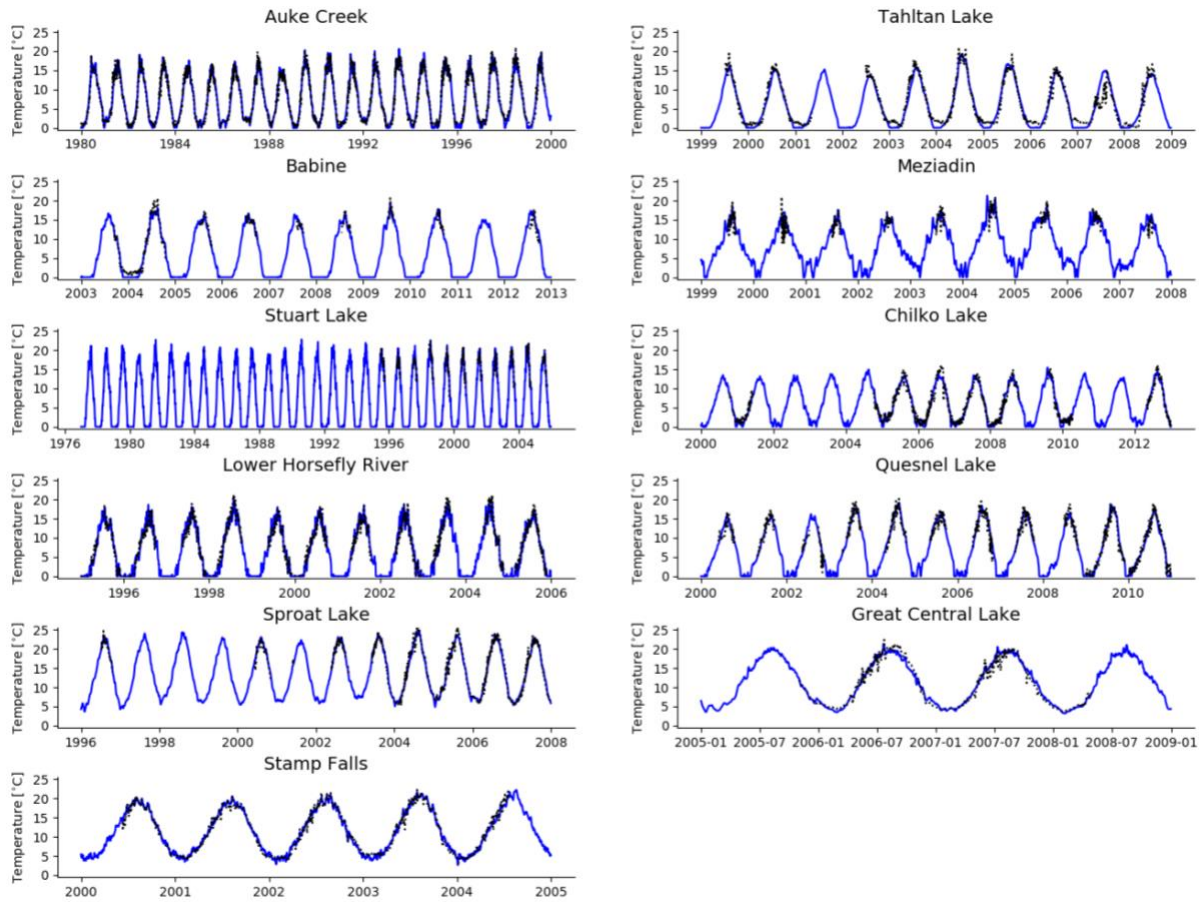


Figure 12. Water temperature validation

4 References

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Appendix A – Static Vegetation Parameters

Table A1. Vegetation / Land Use Parameters set a priori by class

Attribute	MAX _HT	MAX _LAI	MAX_LEAF _COND	IMPERM	FORES T_COV	UBC_ICEP T_FACTOR	FOREST_PET _CORR	ROUGH NESS	SAI_HT_R ATIO	ALBE DO
Units	m	none	mm/s	frac	frac	-	-	m	-	-
NTESP1	16	1.56	5.0	0.034646	1	0.74	1	2.05	2	0.1
NTESP2	18	2.36	5.6	0.063331	1	0.82	1	1.95	2	0.09
NTESP3	23	3.28	7.2	0.063331	1	0.84	1	2.19	2	0.09
NTESP4	29	4.17	9.1	0.034646	1	0.82	1	2.51	2	0.09
NSPTA	11	1	5	0.076816	1	0.84	1	1.36	2	0.11
BETRSR	26	5.38	1.25	0.076816	1	0.87	1	1.93	2	0.15
BDTRSR	16	5.38	1.25	0.076816	1	0.87	1	1.19	2	0.15
BDTESP	16	3.22	1.25	0.076816	1	0.33	1	1.27	2	0.17
MF	15	2.81	5	0.076816	1	0.49	1	1.78	2	0.12
STRSR	2	1.17	5	0.004299	0	0.50	1	0.19	2.15	0.17
STESP	2	1.17	5	0.004299	0	0.50	1	0.19	2.15	0.17
GTRSR	1	0.86	2.5	0.002752	0	0.53	1	0.1	3.7	0.2
GTESP	1	0.86	2.5	0.002752	0	0.53	1	0.1	3.7	0.2
SLMSPP	1	1.32	5	0.076816	0	0.61	1	0.12	2.15	0.16
GLMSPP	0.25	0.88	2.5	0.076816	0	0.61	1	0.03	3.7	0.19
BALMSPP	0.1	0.4	2.5	0.331291	0	1.00	1	0.02	0.1	0.2
WET	2	1.67	2.5	0	0	0.63	1	0.24	0	0.16
CROP	1	2.03	2.5	0.002752	0	0.28	1	0.04	0.7	0.2
BARREN	0.1	0	0	1	0	0	0	0.01	0	0.21
URBAN	11	2.05	0	1	0	0.63	1	1.28	0	0.12
WATER	0.05	0	0	0	0	0	0	0.01	0	0.07
GLACIER	0.05	0	0	0.95	0	0	0	0.01	0	0.65

Table A2. Seasonal Canopy LAI indexes by class

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NTESP1	0.64	0.64	0.64	0.7	0.8	0.9	1	0.81	0.75	0.69	0.64	0.64
NTESP2	0.76	0.76	0.76	0.81	0.85	0.91	1	0.85	0.81	0.76	0.76	0.76
NTESP3	0.76	0.76	0.76	0.84	0.91	1	1	0.91	0.84	0.76	0.76	0.76
NTESP4	0.76	0.76	0.76	0.83	0.9	1	0.97	0.83	0.79	0.76	0.76	0.76
NSPTA	0.72	0.72	0.72	0.79	0.85	0.94	1	1	0.96	0.88	0.76	0.72
BETRSR	0.8	0.8	0.8	0.86	0.93	1	1	0.93	0.86	0.8	0.8	0.8
BDTRSR	0.8	0.8	0.8	0.86	0.93	1	1	0.93	0.86	0.8	0.8	0.8
BDTESP	0.06	0.06	0.06	0.16	0.42	0.86	1	0.72	0.25	0.19	0.06	0.06
MF	0.31	0.31	0.31	0.4	0.49	0.88	1	0.72	0.53	0.34	0.31	0.31
STRSR	0.21	0.21	0.21	0.42	0.77	0.96	1	0.89	0.63	0.21	0.21	0.21
STESP	0.21	0.21	0.21	0.42	0.77	0.96	1	0.89	0.63	0.21	0.21	0.21
GTRSR	0.32	0.32	0.32	0.54	0.75	1	0.97	0.7	0.38	0.38	0.32	0.32
GTESP	0.32	0.32	0.32	0.54	0.75	1	0.97	0.7	0.38	0.38	0.32	0.32
SLMSPP	0.36	0.36	0.36	0.52	0.69	0.9	1	0.98	0.84	0.58	0.36	0.36
GLMSPP	0.45	0.45	0.45	0.52	0.59	0.85	1	0.86	0.69	0.57	0.45	0.45
BALMSPP	1	1	1	1	1	1	1	1	1	1	1	1
WET	0.41	0.41	0.41	0.5	0.78	0.95	1	0.93	0.73	0.57	0.41	0.41
CROP	0	0.05	0.1	0.11	0.26	0.77	1	0.72	0.2	0.11	0.06	0
BARREN	0	0	0	0	0	0	0	0	0	0	0	0
URBAN	0.37	0.37	0.41	0.71	0.9	1	0.99	0.89	0.68	0.53	0.37	0.37
WATER	0	0	0	0	0	0	0	0	0	0	0	0
GLACIER	0	0	0	0	0	0	0	0	0	0	0	0

Appendix B – Surprise Creek headwaters to Meziadin Basin

Surprise Creek is a 218 km² watershed in the headwaters of the Meziadin basin in northwest BC. At a resolution of 500 m x 500 m the watershed is made up of 888 HRUs. Surprise Creek has no lakes. High elevations are suitable conditions for glaciers. Circa 1985, this watershed had 19% glacier coverage by area (Table B1, Figure B1). Calibration runs, 1981 to 2012, were initialized in 1981 with the UNBC 1985 glacier area and tested against glacier area in 2005 also from UNBC (Table B2). Validation runs, simulated over the full PNWNAmet record, 1945 to 2012, were initialized in 1945 with the CRU 1945 glacier area (Figure B2).

Table B1. Statistics on Surprise Creek

Surprise Creek near the Mouth	08DA005
Watershed area	218 km ² (19% glacier coverage 1985)
No. of HRUs	888
Resolution	500 m x 500 m
Raven initialized glacier area 1945	50.25 km ² (201 glacier HRUs x 0.25 km ²)
Raven initialized glacier area 1981	41.75 km ² (167 glacier HRUs x 0.25 km ²)
Glacier area 1945 CRU	50.25 km ² (23.0%)
Glacier area 1985 UNBC	41.2 km ² (18.9%)
Glacier area 2005 UNBC	36.1 km ² (16.6%)
Glacier area lost 1945 to 2005 UNBC	-14.15 km ²
Glacier area lost 1985 to 2005 UNBC	-5.1 km ²

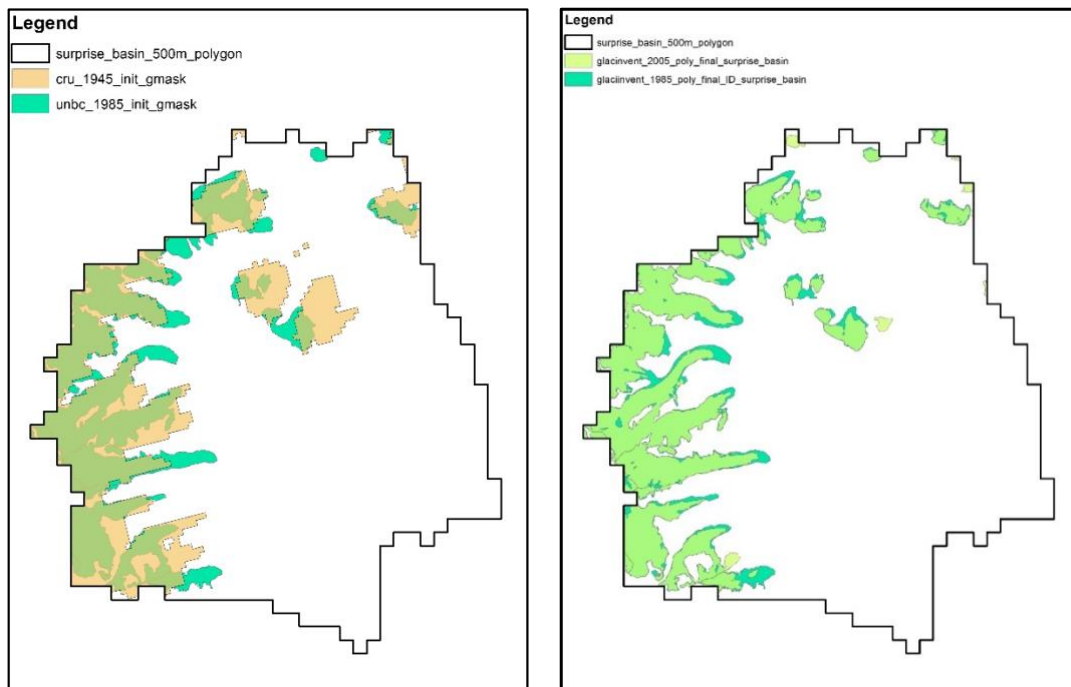


Figure B1. Glacier masks in Surprise Creek (left) CRU 1945 vs. UNBC 1985 (right) UNBC 1985 vs. 2005.

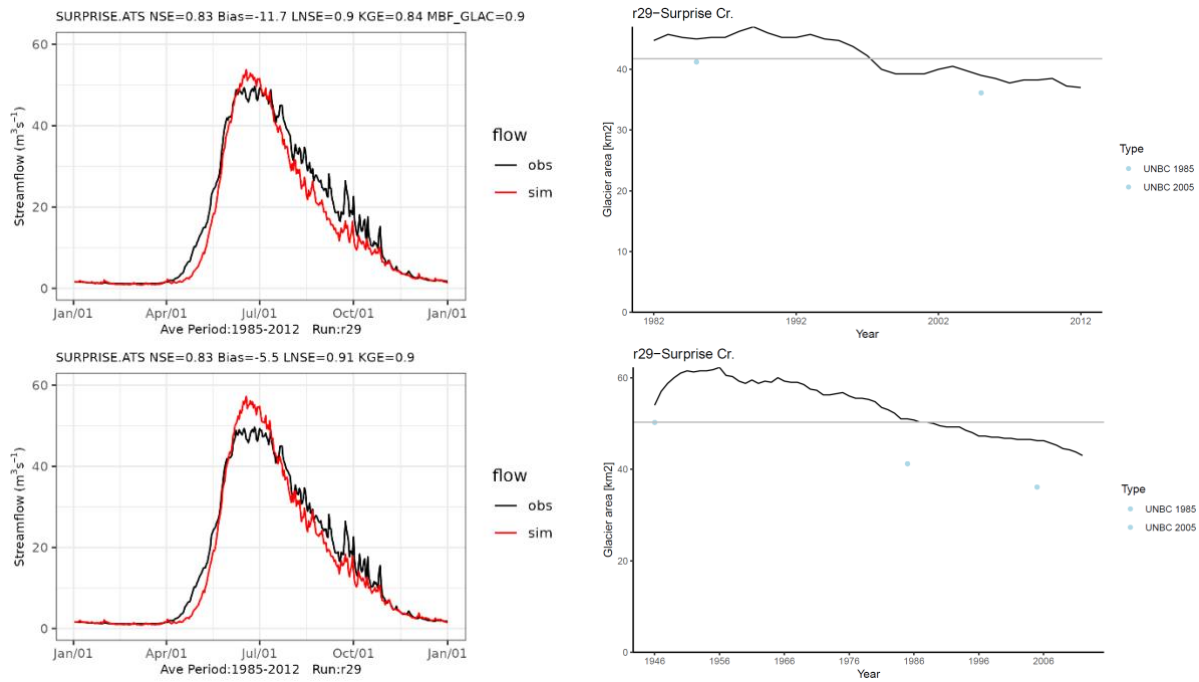


Figure B2. Surprise Creek calibration run (top) and full PNWNAmet run (bottom) average daily streamflow 1985 to 2012 (left) and annual glacier area (right) for selected run, r29 of calib.27Jul.

Table B2. Range in NSE, PBIAS, LNSE and KGE in Surprise when fifth objective function of glacier area is added to the calibration.

	NSE	Bias	LNSE	KGE	Absolute Glacier Area Difference
Min	0.74	-13.86	0.83	0.82	0.1
Max	0.84	-4.26	0.91	0.90	22.2
Mean	0.81	-9.14	0.88	0.86	8.8