Yukon River Basin Streamflow Forecasting System

Centre for Hydrology Report No. 16

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Executive summary

The Yukon River Basin is one of the main rivers in the Arctic region of North America and is shared between Canada and the US. The Canadian part covers almost half of the Yukon Territory in addition to a small portion of the province of British Columbia, while the US part falls totally within the state of Alaska. This study is concerned with Canadian part of the Yukon River with its outlet at Eagle, just across the border in Alaska. Small parts of this catchment are in Alaska. This basin has an area of 288,000 km^2, from 58.8 – 65.6°N and 129.2 – 134.1°W. The southern part of the basin is characterized by large glaciers at high elevations (up to 4700 m above sea level) with steep slopes, and thus generates considerable runoff. There are also mountain ranges on the eastern and northern boundaries of the basin, while the western areas are milder in slope and partially forested. Snow redistribution, snowmelt, glacier melt and frozen soil processes in winter and spring along with summertime rainfall-runoff and evapotranspiration processes are thus key to the simulation of streamflow in the basin.

This project developed, set up, calibrated, validated, and operationalized a streamflow discharge forecasting system for the Yukon River and several of its tributary rivers within the Yukon Territory. The Yukon River Basin streamflow forecasting system is based around the MESH (Modélisation Environmentale Communautaire - Surface and Hydrology) hydrological land surface model. MESH is a state-of-the-art semi-distributed cold regions hydrological land surface model that models both the vertical exchanges of heat and moisture between the land surface and the atmosphere as well has the horizontal transfer of water to streams that is routed hydrologically to the outlet of the basin. It includes snow, frozen soil and glacier processes as well as the full suite of warm season hydrology. MESH is driven by the Environment and Climate Change Canada GEM weather model and hindcasts are driven by GEM-CaPA which is a data assimilation product that uses local precipitation observations where they exist. The rivers forecasted includes the Yukon River Basin upstream of Eagle, AK and the Porcupine River Basin near the international boundary. MESH provides supplemental high resolution simulations and forecasts for the Klondike, Stewart, Pelly and White Rivers at their mouths.

Daily river discharge and water balance forecasts are produced by the system for each river basin. Having MESH run at both 10 km and 5 km resolution provides an assessment of model resolution needed for forecasting and also of model uncertainty in the forecasts. The MESH model was driven by GEM-CaPA for hindcasts and with the GEM ECCC Regional and Global Deterministic Prediction Systems - RDPS and GDPS forecasts for forecasts of 2 and 9 days. The GEM-MESH model showed good to very good predictions in most river basins after calibration and parameter selection, with challenges for the Porcupine and White rivers due to permafrost and wetlands (Porcupine) and to extensive icefields (White) and overall to sparse to non-existent observed precipitation data to assimilate into the CaPA system. The forecast system is capable of providing reliable streamflow predictions and is run with automated scripts on Amazon Web Services.

Future development of the forecasting system should focus on the very challenging permafrost hydrology of the Porcupine River Basin, and the glacier hydrology of the White River which drains the largest icefields in North America. The model does not include a river ice component, but one could be added in the future.

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1. Introduction and Background

The Yukon River Basin is fifth largest basin in North America with an area of more than 850,000 km^2, about 324,000 km^2 of which lies in Canada. The river originates from the Llewellyn Glacier and flows northwest along a 3,185 km course to discharge into the Bering Sea. The Canadian part covers most of the Yukon Territory in addition to a small portion in the north of British Columbia while the US part falls totally within the state of Alaska (Figure 1). The objective of this study is to assist the Water Resources Branch of Yukon Environment in the prediction of river discharge and peak streamflows in the Yukon River system. This study is concerned with the Canadian part of the Yukon River with its outlet at Eagle (denoted Main Yukon), just across the border in Alaska, in addition to the Porcupine tributary with its outlet near the international border, to the north of the Main Yukon basin. Small parts of both catchments are in Alaska. The Main Yukon basin (till Eagle) extends between 58.8 – 64.9°N and 129.1 – 143.9°W and has an area of about 288,000 km^2. The Porcupine River basin extends between 65.3 – 68.7°N and 135.9 – 141.8°W and has an area of about 58,900 km^2. The purpose of this report is to document the development process of the hydrological models for the Main Yukon Basin, the Porcupine River basin, and 4 major sub-basins of the Main Yukon (Pelly, Stewart, Klondike, and White) that are to be used for streamflow forecasting purposes. There are 9 designated forecast points as detailed in Table 1 and Figure 2 (Main Yukon) and Figure 3 (Porcupine).

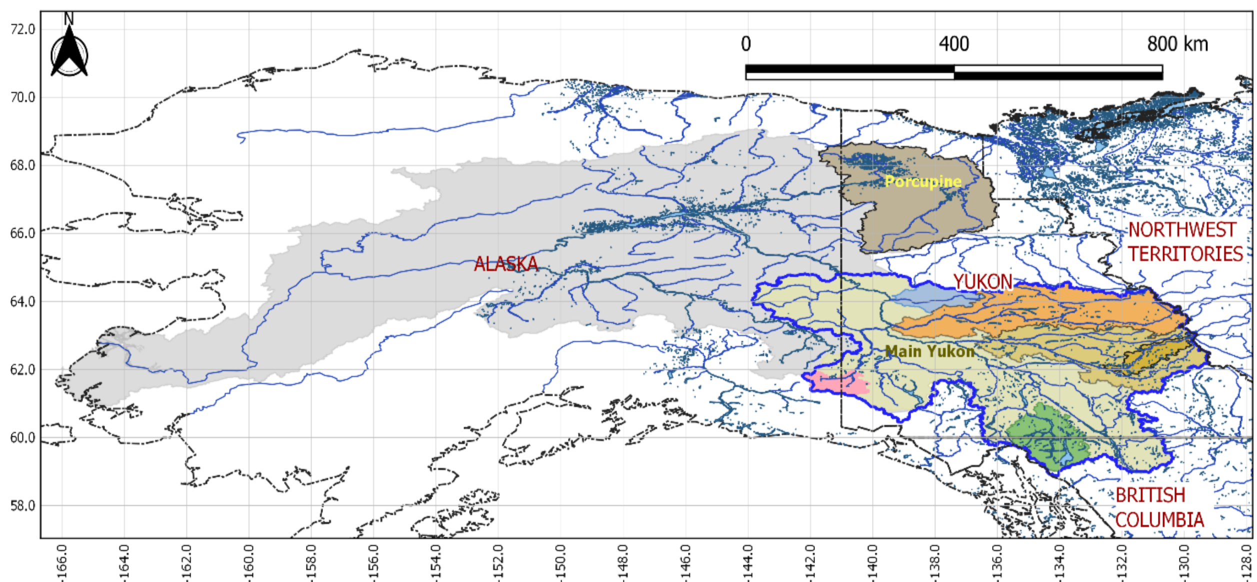


Figure 1: The Yukon River Basin

Table 1: Designated Forecast Points

Station ID	Station Name	Sub-basin (Main)	Area (km²)
09AB001	Yukon River at Whitehorse	Upper Yukon	19,552
09BA001	Ross River at Ross River	Ross (Pelly)	7,306
09BC001	Pelly River at Pelly Crossing	Pelly	48,867
09CB001	White River at Kilometre 1881.6 Alaska Highway	Upper White (White)	6,233
09DD003	Stewart River at The Mouth	Stewart	51,023
09EA003	Klondike River above Bonanza Creek	Klondike	7,814
09EB001	Yukon River at Dawson	Main Yukon	264,000
09ED001	Yukon River at Eagle	Main Yukon	288,071
09FD002	Porcupine River near International Boundary	Porcupine	58,900

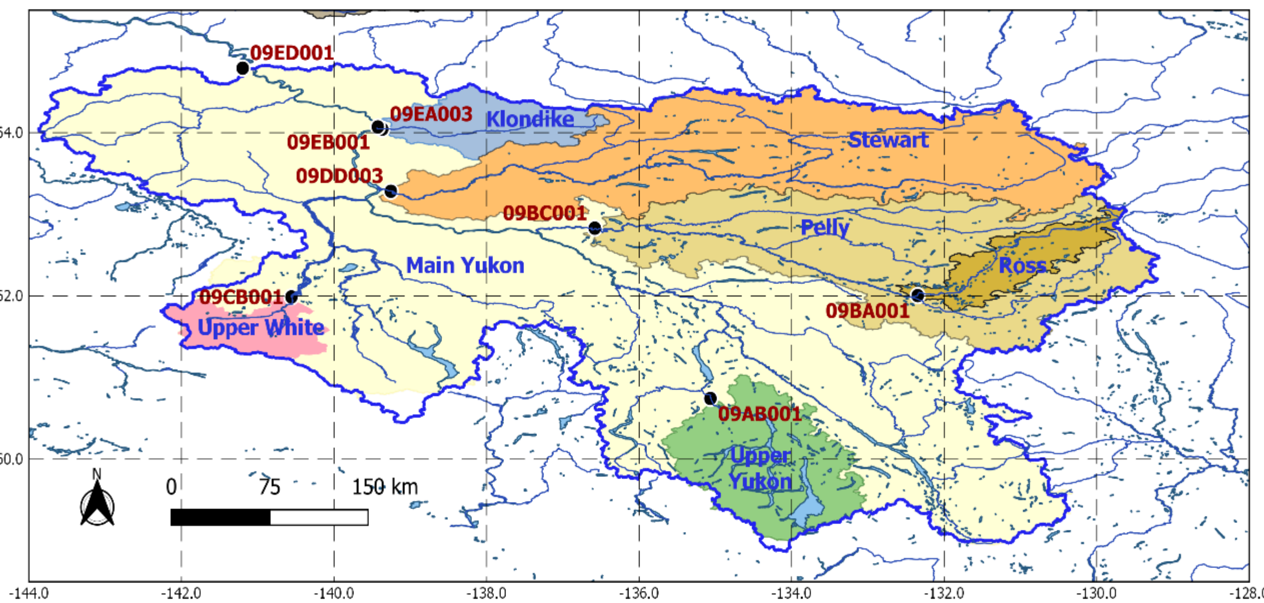


Figure 2: Location of Forecast Points in the Main Yukon River Basin

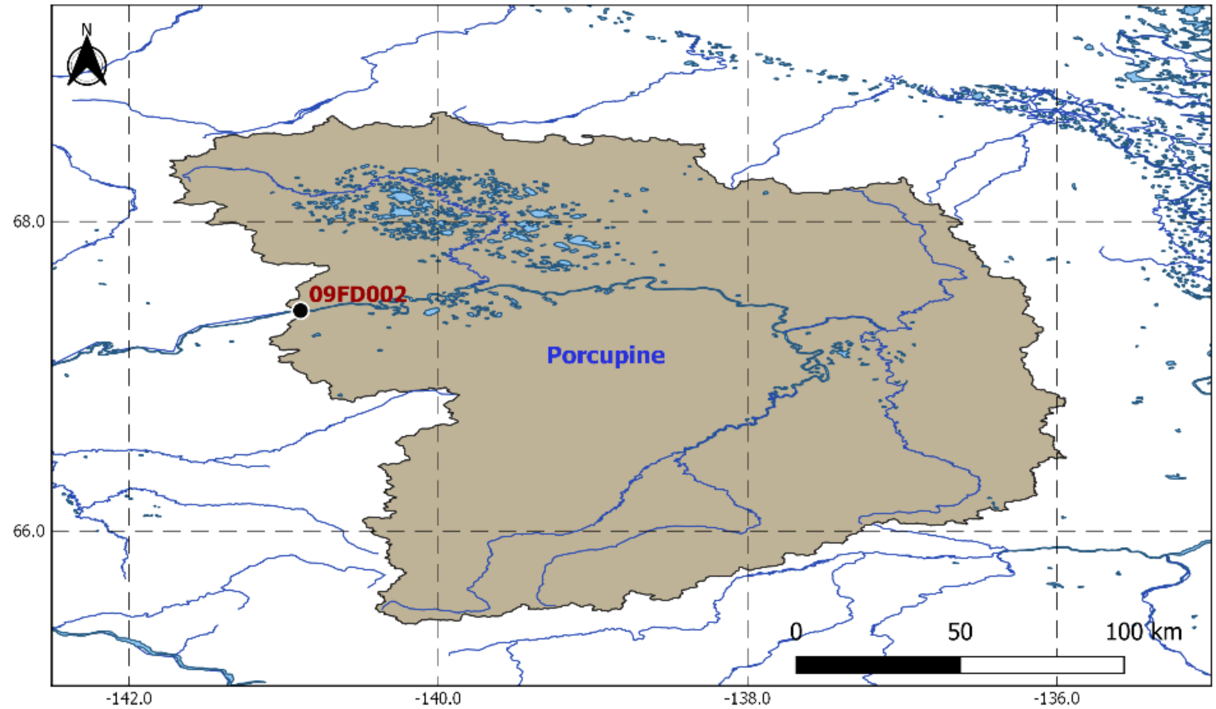


Figure 3: Location of Forecast Point in the Porcupine River Basin

2. Objectives and Approach

This work aims to set up, calibrate and validate, and operationalize a discharge forecasting system for the Yukon River and several of its tributary rivers within the Yukon Territory. The system relies on the MESH (Modélisation Environmentale Communautaire - Surface and Hydrology (Pietroniro et al., 2007)) model to be configured and parameterized for the Main Yukon (and some of its main sub-basins) and the Porcupine basins. When run in forecast mode, the system utilizes the RDPS and GDPS forecasts produced by the GEM - Global Environmental Multiscale (Côté et al., 1998) weather forecast system of ECCC on daily basis for a forecast total lead time of 9 days to provide a deterministic streamflow forecast. Therefore, the GEM-CaPA (Canadian Precipitation Analysis - (Mahfouf et al., 2007)) climatic forcing data will be used during the model development phase as the most compatible dataset with GEM meteorological forecasts.

3. Methodology: Models and Datasets

MESH is a community hydrological land surface model (H-LSM) coupled with two-dimensional hydrological routing (Pietroniro et al., 2007). It has been widely used in Canada to study the Great Lakes Basin (Haghnegahdar et al., 2015) and the Saskatchewan River Basin (Yassin et al., 2017, 2019) amongst others. The MESH framework allows coupling of a land surface model, either CLASS (Verseghy, 2012) or SVS (Husain et al., 2016) that simulates the vertical processes of heat and moisture flux transfers between the land surface and the atmosphere, with a horizontal routing component (WATROUTE) taken from the distributed hydrological model WATFLOOD (Kouwen, 1988). Unlike many land surface models, the vertical column in MESH has a slope that allows for lateral transfer of overland flow and interflow (Soulis et al., 2000) to an assumed stream within each grid cell of the model. MESH usually uses a regular latitude-longitude grid and represents sub-grid heterogeneity using the grouped response unit (GRU) approach (Kouwen et al., 1993) which makes it semi-distributed. In the GRU approach, different land covers within a grid cell do not have a specific location and common land covers in adjacent cells share a set of parameters, which simplifies basin characterization and model parameterisation. While land cover classes are typically used to define a GRU, other factors can be included in the definition such as soil type, slope, aspect. For this application, we used CLASS as the underlying land surface model for MESH and limited the definition of GRUs to land cover classes but the setup was readied to use slope/aspect as well. A full description of MESH physics and basin discretization is given by Pomeroy et al. (2016).

Table 2 lists the datasets used to delineate the catchments and configure the models for the various sub-basins.

Table 2: Spatial Datasets Used/Considered

Dataset	**Source/Description**	**Reference**
Digital Elevation Model (DEM)	Hydrologically conditioned MERIT-hydro	Yamazaki et al. (2019)
Land Cover	2010 Land Cover of North America at 250 meters (MODIS) v1.0	CCRS et al. (2013)
	2010 Land Cover of North America at 30 meters (LANDSAT) v1.0	CCRS et al. (2017)
Soil Texture	Global Soil Database for Earth System Modelling	Shangguan et al. (2014)
Climatic Forcing	Global Multiscale Model (GEM) with precipitation replaced by the Canadian Precipitation Analysis (CaPA)	(Côté et al., 1998) (Mahfouf et al., 2007)

The MERIT-Hydro DEM (Figure 4) has a resolution of 3 arc-sec (about 90m at the equator) and is hydrologically corrected to global river channel data (Yamazaki et al., 2019). The land cover data (both versions) have 19 land cover classes (Figure 5). 8 classes are considered for this study as some land cover classes are not present in the region (tropical land cover classes) while others are grouped to optimize the number of GRUs. The final eight land cover classes are: Alpine (grouping barrenland and Urban), Glaciers, Grass/Shrubs (grouping different types of grasses and shrubs), Water (for water bodies including lakes, reservoirs, and rivers), Wetlands, Needleleaf forest, Mixed forest, and

Broadleaf forest. Further classification to differentiate GRUs based on slope/aspect was conducted but was found not to improve the results significantly because of the selected model resolution. The parameter files are ready to use and the option can be switched on easily.

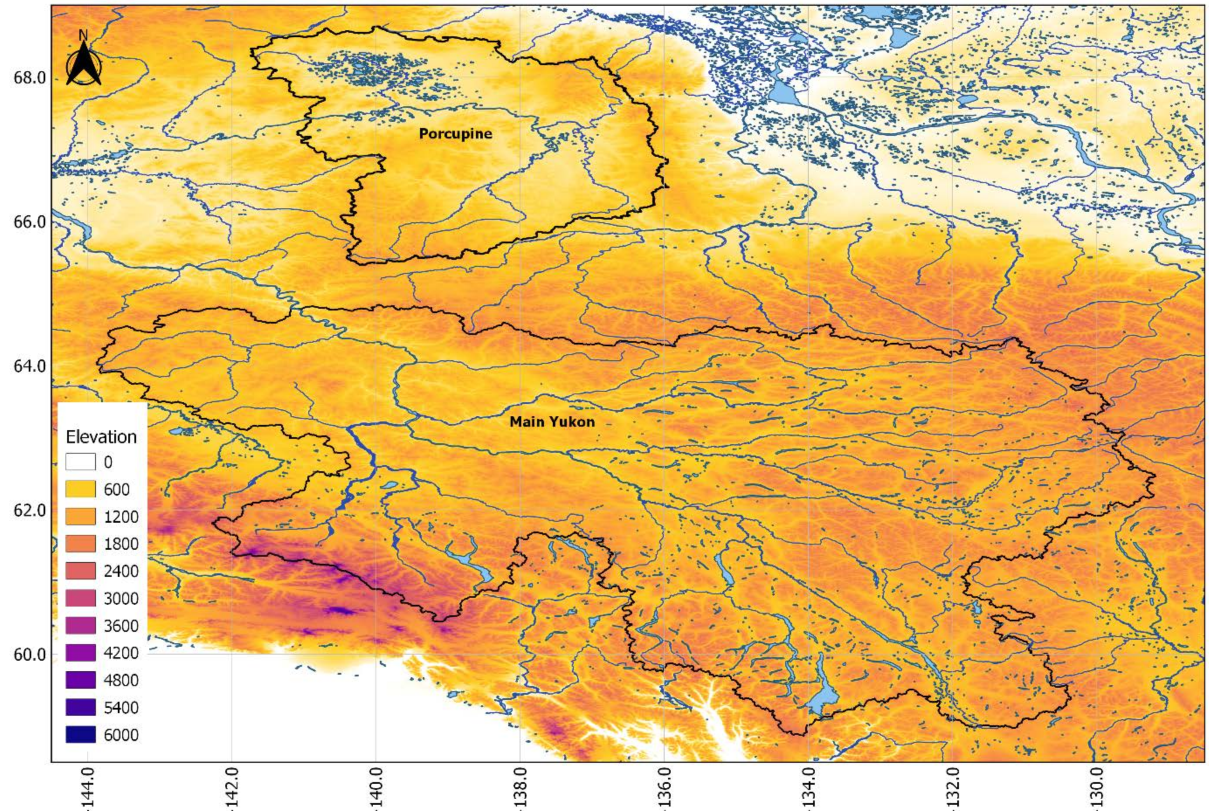


Figure 4: Elevation Map of the Main Yukon & Porcupine sub-basins based on the MERIT-Hydro DEM

MESH/CLASS requires soil hydraulic and thermal parameters which are usually calculated from soil texture parameters (%SAND, %CLAY, and %ORGM). Distributed soil texture was obtained and processed from the GSDE dataset which provides soil gridded texture data for 8 layers down to a depth of 2.3m at a resolution of 1 km. A discontinuity was found in this dataset at the Canadian-US border (see Figure 6 for an example). Therefore, soil texture parameters were calibrated assuming uniform soil for the column depth (4m) but allowed to vary by GRU. The soil column was set to 4 layers, with thicknesses 0.10, 0.25, 1.65, and 2m going from top to bottom. The GSDE dataset provided guidance for the parameter ranges (%SAND and %CLAY) used for the Main Yukon basin and the sparse presence of organic soils in the area was such that organic soils were not considered.

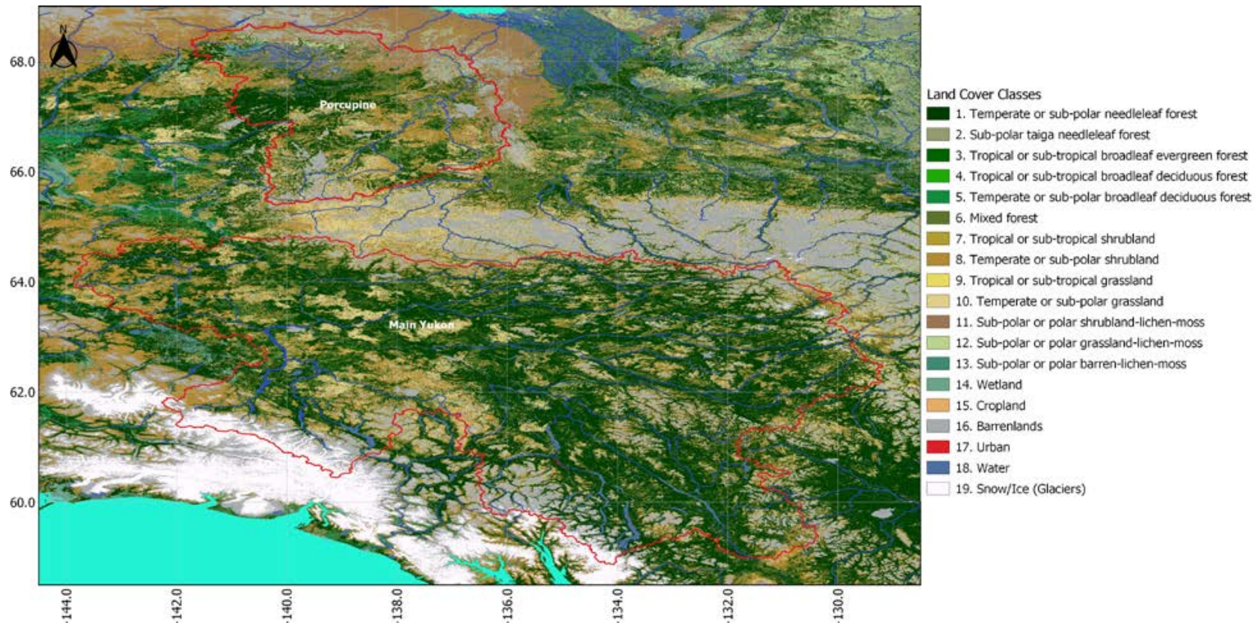


Figure 5: Land Cover Data for the Main Yukon & Porcupine sub-basins based on 2010 NALC LANDSAT 30m Dataset

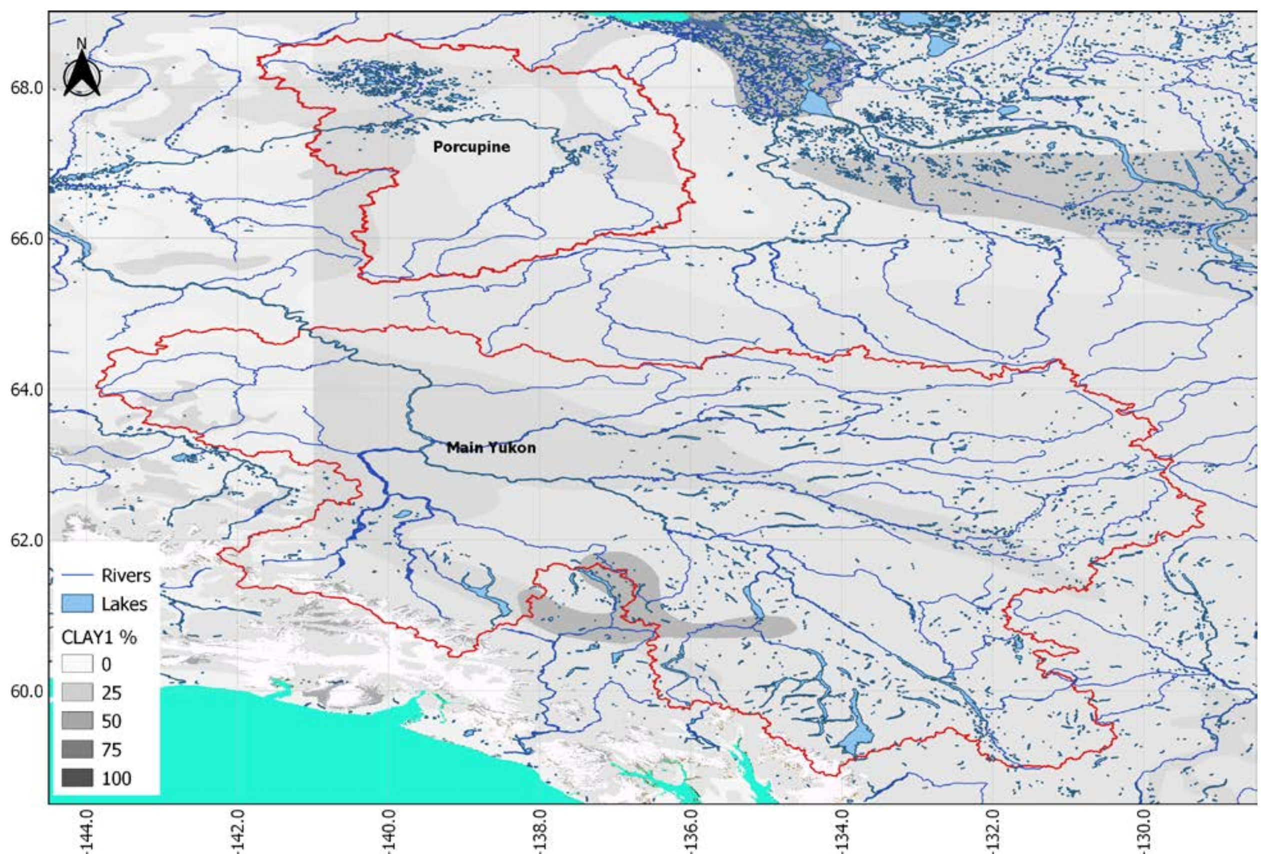


Figure 6: %CLAY in the topmost layer for the Main Yukon & Porcupine sub-basins based on the GSDE dataset

MESH requires 7 forcing meteorological variables to run as detailed in Table 3. The combined GEM-CaPA dataset is used to force the model for calibration and validation as the same dataset will be used for forecasting.

Table 3 Meteorological Variables used in MESH

Variable	**Units**	**Height**
Incoming shortwave radiation	W m^{-2}	Surface
Incoming longwave radiation	W m^{-2}	Surface
Total precipitation rate	kg m^{-2} s^{-1}	Surface
Air temperature	K	40m
Wind speed	m s^{-1}	40m
Barometric pressure	Pa	Surface
Specific humidity	kg kg^{-1}	40m

4. Model Setup for the Main Yukon

4.1 Basin Delineation and Definition of GRUs

Using the MERIT-hydro DEM (Figure 4), the Main Yukon basin was delineated with Eagle (Station 09ED001) as the outlet using a regular latitude-longitude grid with a spatial resolution of 0.125° (~10km). The Green Kenue software (Canadian Hydraulics Center, 2010) was utilized for processing the DEM and land cover data to produce the shed file and then the drainage database. This yielded a grid with 120 columns, 56 rows and 3,448 active grid cells for the basin.

Land cover fractions were calculated based on the high resolution 30m LANDSAT version of the 2010 NALC dataset (Ref). The 19 land cover classes of the 2010 NALC dataset were grouped into 8 land cover classes as mentioned above. The terrain was classified as flat (slope < 10°) and steep (slope > 10°). Steep slope is further classified as south facing (aspect is between 180 to 270°) and north facing slope where aspect lies elsewhere. Alpine and Grass/Shrubs GRUs are further segregated based on slope and aspect and become (flat, north and south facing) and thus the total number of GRUs is 12. The distribution of the different GRUs for the Main Yukon basin are listed in Table 4. In total, the basin has 24,470 tiles (computational elements).

Table 4: GRU Fractions for the Main Yukon basin

	GRU	%
1	Alpine SF	3.55
2	Alpine NF	3.14
3	Alpine flat	2.22
4	Glacier	1.98
5	Grass/Shrubs SF	7.87
6	Grass/Shrubs NF	4.47
7	Grass/Shrubs flat	15.76
8	Water	2.81
9	Wetland	0.47
10	Needleleaf forest	48.96
11	Mixed forest	7.24
12	Broadleaf forest	1.52

The basin is mostly forested (49% Needleleaf forest in addition to about 9% mixed and broadleaf forests). The second most important land cover is grass/shrubs (about 28% in total) followed by alpine areas (~9% in total). About 2% of the basin is covered with glaciers but they are important for southern tributaries. Less than 3% is covered by water bodies (mainly lakes) but they still exert a lot of control on the flow of the sub-basins where they exist (Upper Yukon, Teslin, Takhini, and White). Parameters for the dominant GRUs will be used for calibration.

The next step before parameterization is to verify that drainage directions are generally correct. This is done to insure that the delineated drainage areas of sub-basins are as accurate as possible and that the delineated boundaries are as close as possible to the WSC shape files. For this shapefiles for 25 sub-basins were collected from WSC in addition to 36 sub-basins (some of them are discontinued gauges) where the HYDAT database report the drainage areas but the shape files are not available (Figure 7). Drainage directions were manually edited to correct the areas. A number of iterations were done until the modelled sub-basin areas and shapes became in good agreement with WSC shapefiles. Agreement is defined by area error tolerances that are inversely proportional to sub-basin size as given in Table 5. The rationale is that smaller sub-basins are more difficult to be accurately represented at the selected resolution than larger basins encompassing many more gridcells. A higher resolution would allow more strict tolerances.

Table 5: Area Error Tolerances based on Drainage Area

Drainage Area	Size Category	Error Tolerance
> 100,000 km^2	Extra Large	1%
3,000 – 100,000 km^2	Large	5%
1,000 – 3,000 km^2	Medium	10%
< 1000 km^2	Small	20%

There are three dams in the Main Yukon basin: Whitehorse at the outlet of the Upper Yukon basin, Mayo on the Mayo tributary of the Stewart River, and Faro on Rose Creek, a secondary tributary of the Pelly River. Mayo and Faro dams are small and found to have little effect on flows downstream, especially as they are too far upstream of the Stewart and Pelly outlets (which are forecast points). The Whitehorse dam is also small and has a small immediate reservoir (Schwatka Lake). However, it is connected to a structure downstream the outlet of Marsh Lake where water is stored during late summer/autumn to be utilized for power generation during winter. The Upper Yukon sub-basin has a complex of interconnected lakes that were given proper attention during calibration but the reservoir was not explicitly included as the system response is generally slow. Lakes were considered so as to obtain proper streamflows at Whitehorse to improve the quality of simulations of downstream forecast points (Dawson and Eagle, AK).

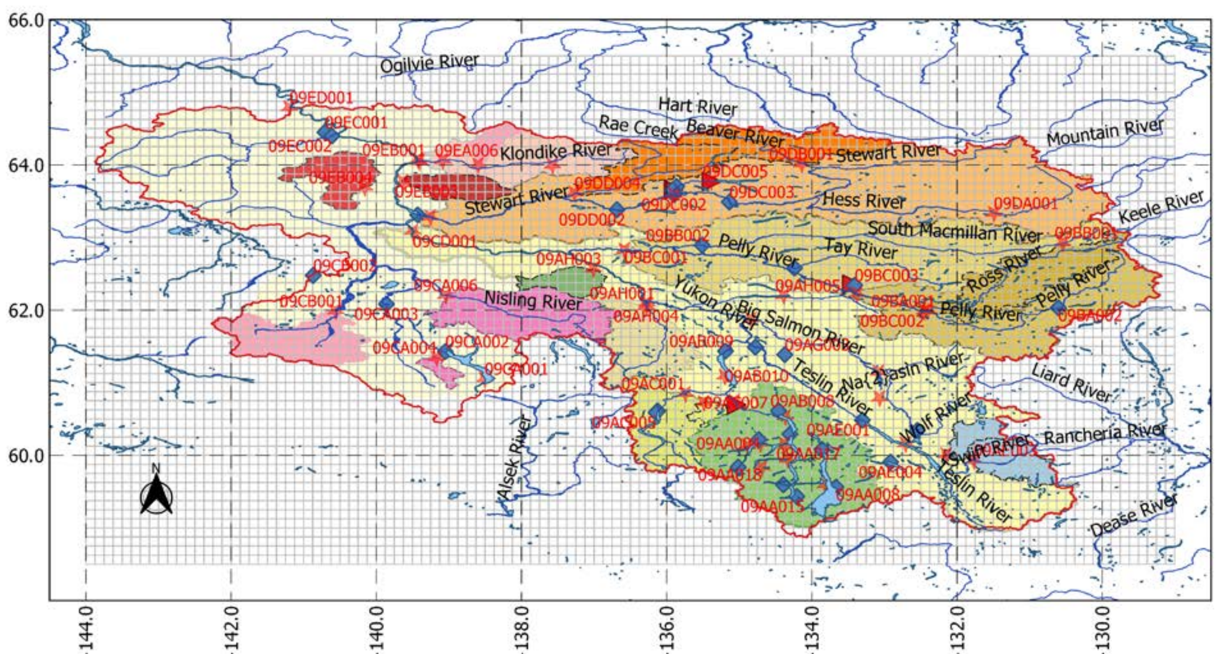


Figure 7: Main Yukon River Basin: Sub-basins, Model Grid, and Gauging Network. Red Stars indicate active gauges, blue diamonds indicate inactive ones, and triangles indicate locations of dams. Model Grid is shown in grey.

4.2 Parameterization Procedure

The next step in the development of the model was to populate the parameter files with reasonable values such that the model replicates the streamflows, mainly at the designated forecast points as much as possible while keeping it physically constrained. Validation against other states and fluxes (e.g. snow depth or SWE, evapotranspiration, soil moisture, etc.) could be performed based on data availability. For the current study, streamflow records were used to calibrate a selected set of sensitive parameters while non-calibrated ones were deduced from previous studies and expert knowledge of MESH.

To maximize the utility of available streamflow gauge records available in the basin, the gauging network and available records were analyzed. The period 2004-2015 was selected for analysis based on the concurrent availability of flow records and climatic forcing. There are 46 active WSC gauges in the basin (Figure 7), 11 of them are measuring levels only (important for lakes) and the remaining 35 measure streamflow. These were further screened based on the completeness of flow records to yield 25 usable streamflow gauging stations. Figure 8 shows a schematic of the river network and indicates the suitable stations for calibration.

There are tributaries (e.g. Pelly and Stewart) that have gauges near their outlets as well as gauges on their upstream tributaries. These allow proper characterization of streamflows along those rivers. Meanwhile, there are other tributaries (e.g. Teslin, White, Big Salmon) where there are some gauged areas in the upper catchments but there is no gauge near their outlets. For these, gauges on the main Yukon will provide some information for calibration. Thus, to maximize the utility of available records, all 25 gauges were used simultaneously but the downstream ones were used to calibrate the incremental areas that were not covered by upstream ones. To do so without giving extra weight to downstream ones (as they have larger flows), the incremental streamflow was converted to areal runoff by dividing it by the upstream catchment area downstream of any gauged sub-basins. To illustrate the idea, consider the Pelly tributary which includes the Ross gauged near its outlet (09BA001). The next gauge with available record is 09BC004 whose catchment area includes the Ross. The incremental runoff at 09BC004 will thus exclude the runoff generated by the Ross because it is nested within the Pelly. The incremental runoff at the outlet of the Pelly (09CB001) excludes what is generated up to 09CB004. This is done progressively for the 25 gauges considered going from upstream to downstream to yield incremental runoff records that are used for calibration after post-processing the simulated streamflows within MESH (code was modified to accommodate that). Figure 9 shows an annual summary map of incremental runoff using the 2004-2015 streamflow records with minimal filling of gaps. It shows the very high runoff generated by the Upper White and the Atlin sub-basins and very low contributions of some other sub-basins (e.g. Nordenskiold).

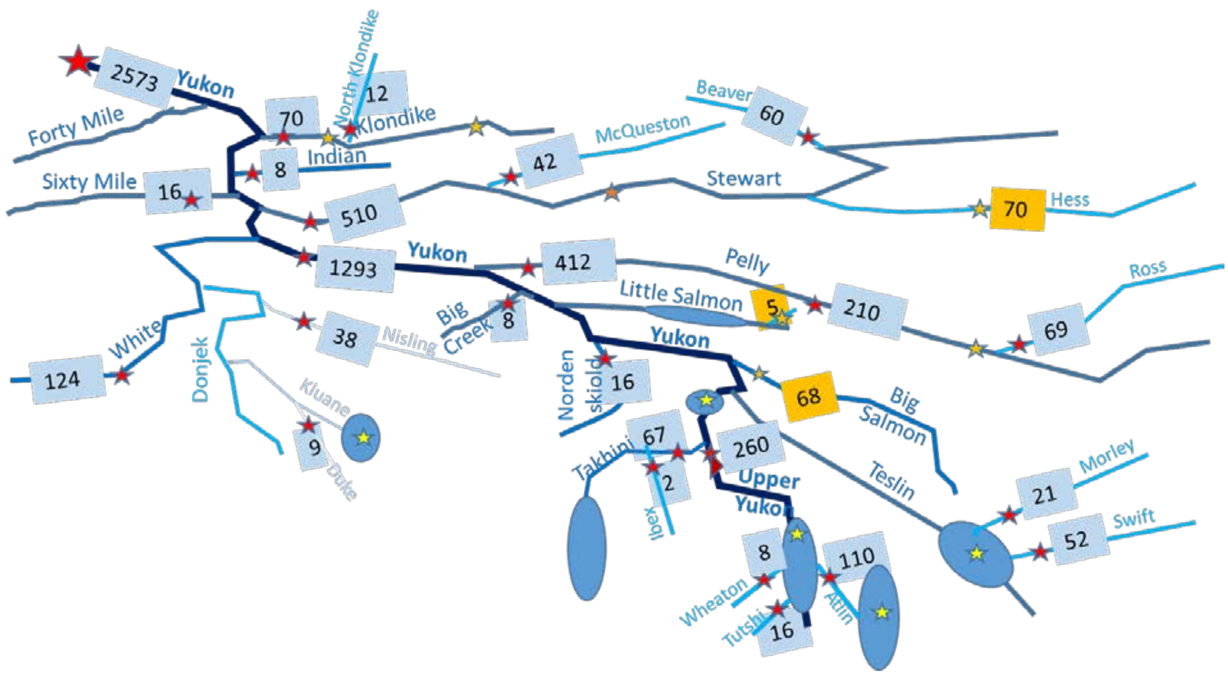


Figure 8: Schematic of the Main Yukon River Basin (up to Eagle). Rectangles show the mean discharge over the 2004-2015 period in m³/s – Blue indicates active gauges and yellow indicates inactive ones where numbers are based on older historical records. Stars show the locations of gauges, red stars (25) indicate flow gauges with records suitable for calibration, yellow stars (11) have level records where some may be useful for characterizing lakes, and orange (1) indicates desirable calibration points where there are no current records. Red Triangles (3) indicate important dam locations.

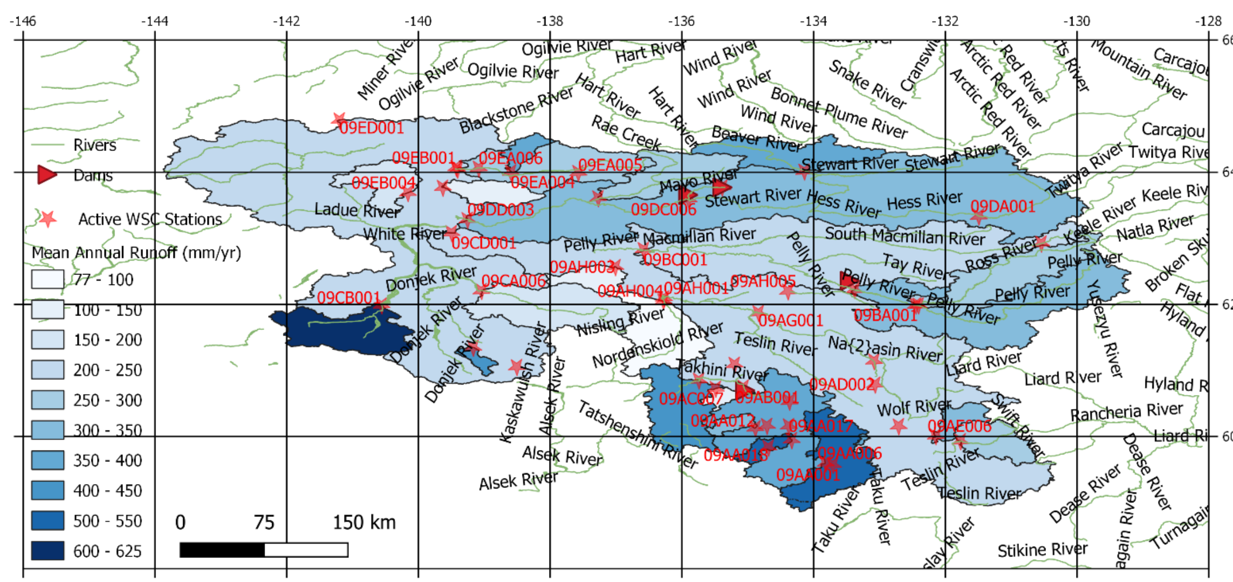


Figure 9: Mean Annual Incremental Runoff (mm/year) by Sub-basin over the 2004-2015 period

This analysis was taken one step further to calculate the runoff ratios over the period 2004-2015 using CaPA precipitation. Incremental runoff ratios (by excluding gauged upstream sub-basins from downstream as explained above) are plotted in Figure 10. This analysis highlighted catchments like Atlin and Upper White where runoff coefficients are exceptionally high (1.003 and 0.855) because of glacier melt, which led to changing some hard-coded glacier parameters (namely albedos) in order to achieve proper flow simulations. Sub-basins with very low runoff ratios (e.g. Nordenskiold) are diagnosed as well where the reason is not low precipitation but rather sluggish rivers.

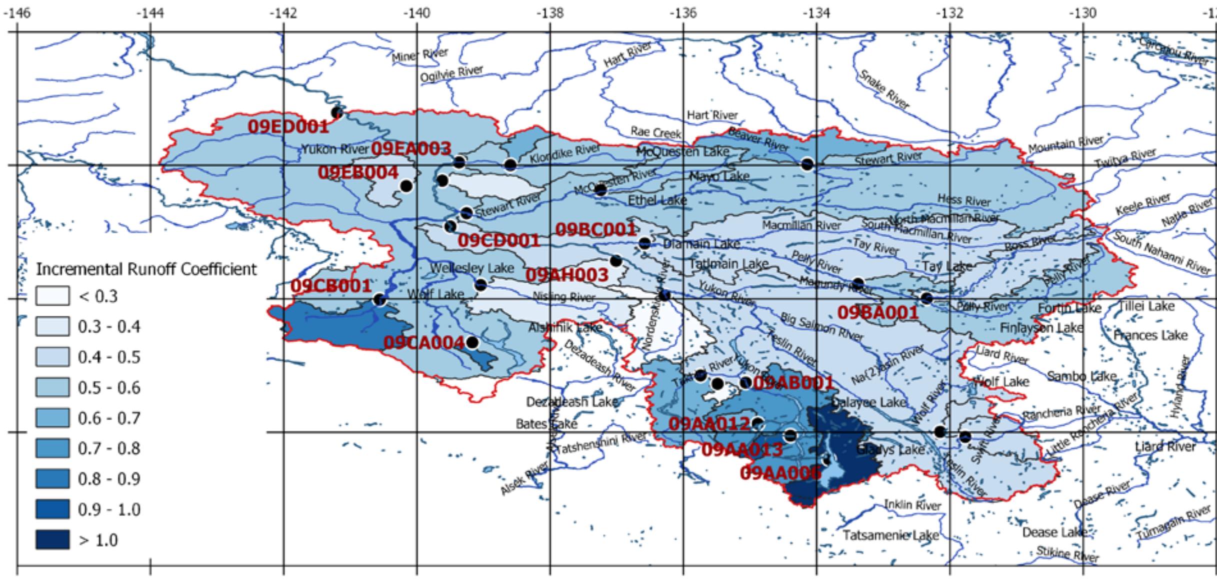


Figure 10: Mean Incremental Runoff Coefficients by Sub-basin over the period 200-2015 (using GEM-CaPA Precipitation and HYDAT flow records with minimal inflilling)

Stage 1: Closing the Water Balance

The model was calibrated automatically in several stages. First, soil texture and a few vegetation parameters were calibrated for the dominant GRUs (Needleleaf Forest, Grass/Shrubs, and Alpine) to minimize PBIAS, in order to close the water balance as much as possible, at various points in the system. The parameter set selected for calibration was limited to a subset of what Haghnegahdar et al. (2017) listed in their analysis as the most sensitive parameters. Parameter ranges were obtained based on previous literature and expert opinion from the adjacent Mackenzie River basin (Table 6). Values for non-calibrated parameters were set in the same way. Calibration was performed using the DDS optimization algorithm (Dynamically Dimensioned Search; Tolson and Shoemaker, 2007) with a budget of 5000 iterations. The total number of parameters for minimizing PBIAS was 27. A pseudo multi-objective approach was used to combine absolute values of PBIAS for the 25 used gauging stations, based on incremental sub-basin runoff contributions as mentioned above. The 2004-2015 record was split into two periods where 2004-2011 was used as a calibration period while 2012-2015 was set as the validation period. To start the evaluation of metrics at the beginning of 2004, the model was initialized on Sep 1, 2004 and run to Dec 31, 2005 as a spinning period saving the initial conditions to be used to start the main simulation from Jan 1, 2004. The initial conditions were fixed from a single run during the calibration but the model was spun again using the calibrated parameters for the final evaluation. The approach yielded results that were superior to calibrating the whole basin to the outlet (Yukon River at Eagle – 09ED001) only. However, some sub-basins with very low performance caused the optimization algorithm to exert more effort to improve them while they were not as important (e.g. Ibex sub-basin – 09AC007) due their small contribution at the main forecast points. Thus, the objective function was later revised to focus on the forecast points only (seven for the Main Yukon after excluding Yukon River at Dawson – 09EB001 as it does not have flow records during the calibration period).

Table 6: Water Balance calibrated parameters and their ranges for GRUs considered for calibration

Parameter	**Unit**	**Description**	**Range by GRU**			
			NL Forest	**Grass/Shrubs**	**Alpine**	**Glacier**
SDEP	m	Soil Permeable Depth	0.5 – 4.0			N/A
SAND*	%	Percent sand in soil	30 – 90			N/A
CLAY*	%	Percent clay in soil	0 – 50			N/A
ROOT	m	Rooting Depth	1.0 – 2.0		N/A	N/A
RSMN	s m^{-1}	Minimum stomatal resistance	150 – 200	75 – 160	N/A	N/A
VPDA	-	Vapour pressure deficit coefficient "A"	0.3 – 0.7		N/A	N/A
ZSNL	m	Min snow depth to consider 100% coverage	0.02 – 0.30			
ZPLS	m	Max. ponding depth on snow covered ground	0.02 – 0.15			
ZPLG	m	Max. ponding depth on snow free ground	0.02 – 0.15			

* %SAND, %CLAY are constrained such that their sum does not exceed 100%. CLASS assumes the remainder as silt if their sum is less than 100%

Stage 2: Routing

Routing parameters for stream channels, overland flow and baseflow components were calibrated to maximize the sum of NSE (Nash-Sutcliffe Efficiency) for the 25 gauges calculated using incremental streamflows as a single objective function. Green Kenue produces one river class for all rivers. Therefore to gain more degrees of freedom for calibration knowing that large rivers are typically different than small streams, 5 river classes were introduced. River classes were categorized based the logarithm of the "bankfull" attribute of the drainage database (denoted B) which is a function of the cumulative drainage area at the considered gridcell. The logarithm transform was done to reduce the range of values. The 5 river classes were mapped based on the quantiles of Log(B) such that the smallest streams (lowest 20% of Log(B) range) are given river class 5, while the largest ones (top 20%) are given class 1 (Figure 11). The number of river classes is arbitrary but using the quantiles reduces the subjectivity of selecting thresholds to differentiate river classes. Each class has it is own values for manning roughness coefficients. Baseflow coefficients were defined based on river classes while overland (within cell routing) manning coefficients are defined at the GRU level. Parameter ranges are considered the same across river classes and GRUs (Table 7).

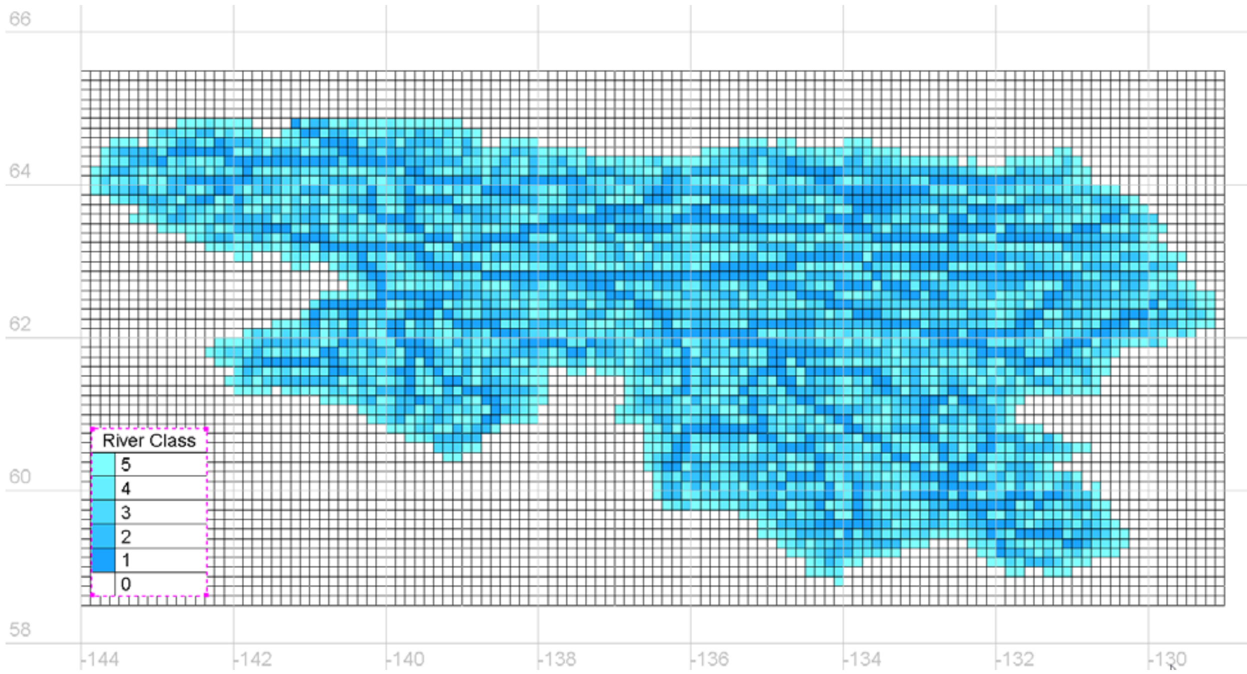


Figure 11: Mapping River Classes for the Main Yukon basin

This yielded 24 parameters and was allocated a calibration budget of 5000 iterations using the DSS algorithm. There could be some interaction between water balance parameters and routing parameters but it is generally small. Obtained PBIAS values after calibrating NSE did not change much.

Table 7: Routing calibrated parameters and their ranges

Parameter	Unit	Description	Range
MANN[i]	$s\ m^{-1/3}$	Manning's "n" for overland flow (within cell)	0.02 – 0.30
R2N[j]		Manning's "n" for channel flow	0.01 – 0.15
K[j]	-	Factor relating overbank flow Manning's "n" to that of channel flow (R1N = k x R2N)	1.2 – 4.0
PWR[j]	-	Exponent of Baseflow Linear Reservoir	1.0 – 3.0
FLZ[j]	-	Coefficient of Baseflow Linear Reservoir	1.0e-8 – 1.0e-2

[i] varying by GRU, 4 major GRUs (Needleleaf, Grass/Shrubs, Alpine, and Glacier) are considered
[j] varying by river class, 5 classes are considered separated at quantiles of Log(Bankfull)

These initial calibrations pointed out several deficiencies in the model and approach that were addressed in later stages:

1- The balance was not closed for a few sub-basins, e.g. Atlin, Kluane, and Upper White had large negative biases (under-estimation of flows of up to 40%) which impacted PBIAS at downstream stations such as Yukon at Whitehorse and Eagle and compensating errors in other sub-basins. This was investigated and we found that glaciers were improperly parameterized with very high albedo values that were producing negligible runoff.

2- The seasonality of flows at several stations was not reproduced due not to including upstream lakes.

Stage 3: Improving Glacier Parameters

To fix the water balance of southern catchments affected by large glaciers (Atlin, Upper White, and Kluane) – see Figure 5, hard-coded glacier albedo parameters were altered. A sensitivity analysis was performed for each sub-basin to determine the albedo values that would eliminate the volume bias as while maintaining physical realism as per previous studies (e.g. Gardner and Sharp, 2010). Albedo values were set to 0.35 and 0.23 for visible and infra-red bands respectively for the Llewellyn glacier feeding Lake Atlin. The St. Elias Icefield and adjacent glaciers (e.g. Donjek, Steele, etc.) feeding the Upper White River Basin was assigned a slightly higher value for the visible albedo of 0.45, while the infrared albedo was set at 0.23 as for the Llewellyn glacier. The Kaskawulsh glacier feeding Kluane Lake and river was assigned albedo values of 0.45 and 0.33 for visible and infrared bands respectively.

Loukili and Pomeroy (2018) studied the retreat of the Kaskawulsh glacier which caused its contribution to divert to eastwards to the Kaskawulsh River which drains to the Alsek river instead of flowing northwards to the Slims river which feeds Lake Kluane. They note that this happened during 2016. Therefore, the drainage database used for the calibration and validation includes the Kaskawulsh glacier contribution to Kluane Lake/River while the drainage database to be used for the forecasting (starting spring 2020) is corrected to divert the contribution of the glacier outside the basin.

Stage 4: Including Lakes

The basin includes several important lakes (Figure 12) that regulate the flow, especially for the southern tributaries (Teslin, Upper Yukon, Takhini, and White sub-basins). After calibrating for PBIAS and then NSE, NSE for several stations only improved by including those lakes. Table 8 lists the lakes that were considered. Lakes are modelled as routing elements in MESH. The drainage database "reach" field was edited to include those lakes by designating the gridcells that belong to each lake by overlaying their shape files with the model grid. At the current model resolution, the representation is not very accurate, especially for finger- and snake-shaped lakes, but still serves the purpose. MESH does not route the flows in lake designated gridcells but accumulates all runoff (generated locally at those cells or routed to them from other cells) at the outlet then applies the outflow equation at the outlet based on the water storage (a rating curve in terms of active storage). MESH uses either a power law or up to a fifth degree polynomial for the outflow equations. For this application, we found the power law performing nicely for all lakes, and is easier to calibrate. Lake outflow equations are calibrated in a spreadsheet to maximize NSE based on the inflows simulated by MESH for each lake separately vs "observed" or "estimated" outflows at outlet gauges. When there is no flow record at the outlet gauges, flows are either estimated using a rating curve or from the nearest downstream gauge based on analysis of available concurrent records, or to minimize volume bias, as detailed in Table 8. If lakes have other lakes upstream, the upstream ones are calibrated first as they modify the inflow pattern going into the downstream ones in the cascade.

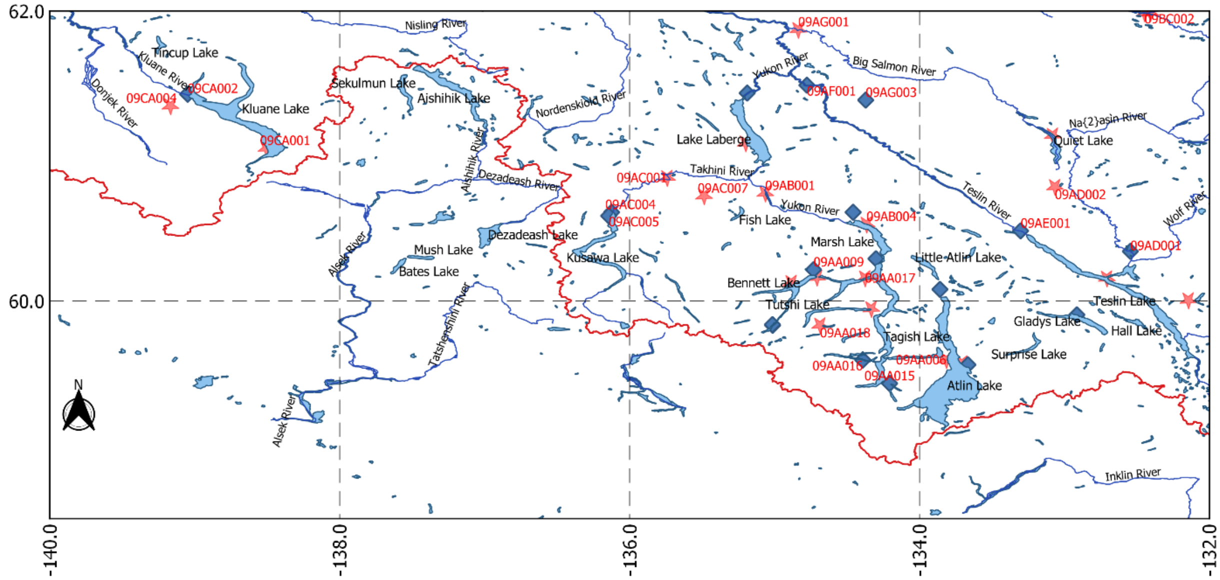


Figure 12: Important Lakes in the Main Yukon and Location of Gauging Stations used to construct their flow records

4.3 Final Parameters and Calibration and Validation Results

The parameterization process was iterative. After including the glacier albedo adjustments and calibrating lake outflow relationships, additional calibration runs were done to re-optimize parameters further taking into account those changes. The final parameter set is documented in Appendix 1. All (8) forecast points in the Main Yukon, except 09EB001 (Yukon River at Dawson), had flow records for the selected calibration/validation periods with minimal gaps. Gaps were not infilled when calculating the metrics but rather skipped. To evaluate the model at station 09EB001 (Yukon River at Dawson) where the observed flow record does not cover the calibration/validation period, a flow record was constructed in two steps (Figure 13). First, an open water rating curve was constructed from concurrent level and flow records (1960-1976) which was used to extend the flow record till mid-1996 when the water level records at Dawson stopped. Correlation between open water flows at Dawson and Eagle was then established for the period 1983-1996 and the relationship was used to extend the record at Dawson till 2016. There is not much contribution between Dawson and Eagle and thus Dawson flows are closely related to those at Eagle. Water level measurements at Dawson were resumed in 2014 and the establishment of an updated rating curve there would further improve the flow estimates at Dawson.

Table 8: Included lakes and information about their flow/level records

ID	**Lake**	**Area (km^2)**	**Upstream Lake(s)**	**Outlet Gauge**	**Remarks**
1	Schwatka	5.95	Marsh	09AB001	Dam operation is not considered
2	Atlin	772.87	-	09AA006	Glacier affected
3	Tutshi	46.71	-	09AA013	
4	Marsh	98.55	Tagish-Bennet	Fictitious	Assumed outflow = 94% of 09AB001 flow based on drainage area ratio between the assumed outlet and 09AB001
5	Tagish (includes Fantail)	377.85	Atlin, Tutshi	Fictitious	Combined as Tagish-Bennet for simplicity and due to lack of outlet gauges or flow records at available gauges. Assumed outlet flow = 87% of 09AB001 flow to minimize PBIAS (between simulated inflow and outflow).
	Bennet (includes Lindeman)	95.97		09AA004	
6	Laberge	204.48	Schwatka, Kusawa	09AB009	Rating curve (open water) constructed from concurrent lake levels at 09AB010 (1980-1994) and used to extend flow records until 2016.
7	Kluane	408.45	-	09CA002	Glacier affected; Glacier retreat; Rating curve (open water) constructed from concurrent historical levels at 09CA001 – see Loukili and Pomeroy (2018) for details.
8	Teslin	363.93	-	09AE001	Rating curve (open water) constructed from concurrent historical levels at 09AE002 (1944-1994) and used to extend flow records until 2017.
9	Kusawa	144.87	-	09AC004	Assumed outflow = 87% of flows at 09AC001 based on analysis of concurrent records (1952-1986). Construction of a rating curve using levels at 09AC005 is possible but not useful as the level records stop in 1986.

Figure 14 shows the streamflow hydrographs for all forecast points for the whole calibration and validation period, which visualizes model performance in all aspects of the simulation (low flow, high flow, timing, and volume). It summarizes the performance over the calibration, validation, and whole period while Figure 15 shows the variation of performance across stations and years in terms of NSE as it is sensitive to flood peaks and timing.

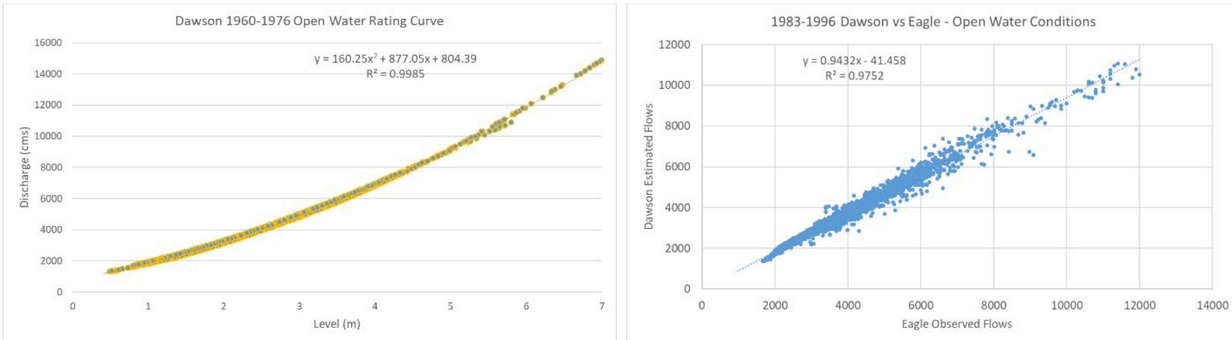


Figure 13: Constructing the flow record at 09EB001 (Yukon River at Dawson)

Table 9: Performance at forecast points for calibration, validation, and whole period and median of annual values over the whole period (metrics calculated individually for each year)

Forecast Point	Calibration 2004-2011		Validation 2012-2015		Overall 2004-2015		Median of Annual values	
	NSE	**PBIAS**	**NSE**	**PBIAS**	**NSE**	**PBIAS**	**NSE**	**PBIAS**
09AB001	0.79	3.8%	0.87	3.0%	0.84	3.5%	0.84	4.7%
09BA001	0.62	14.1%	0.55	16.7%	0.65	15.0%	0.74	15.6%
09BC001	0.76	0.4%	0.74	5.4%	0.79	2.2%	0.77	2.4%
09CB001	0.41	-7.9%	-0.06	16.7%	0.37	1.7%	0.57	3.1%
09DD003	0.46	-3.4%	0.53	-2.5%	0.59	-3.1%	0.70	1.0%
09EA003	0.58	-20.3%	0.56	-18.2%	0.65	-19.5%	0.62	-16.5%
09EB001	0.80	-1.6%	0.79	1.9%	0.83	-0.3%	0.84	0.3%
09ED001	0.81	-3.4%	0.81	0.1%	0.84	-2.2%	0.85	-1.5%

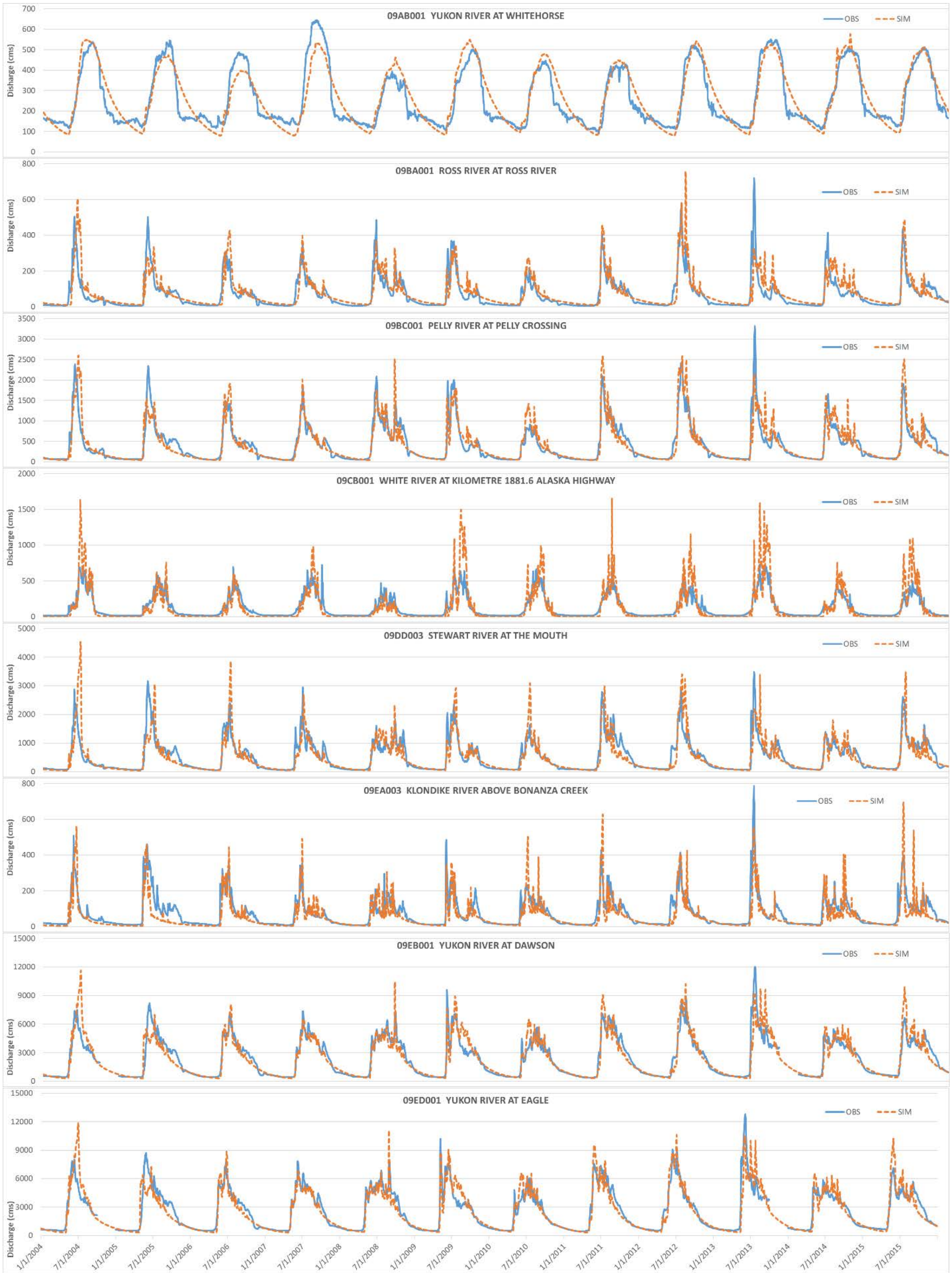
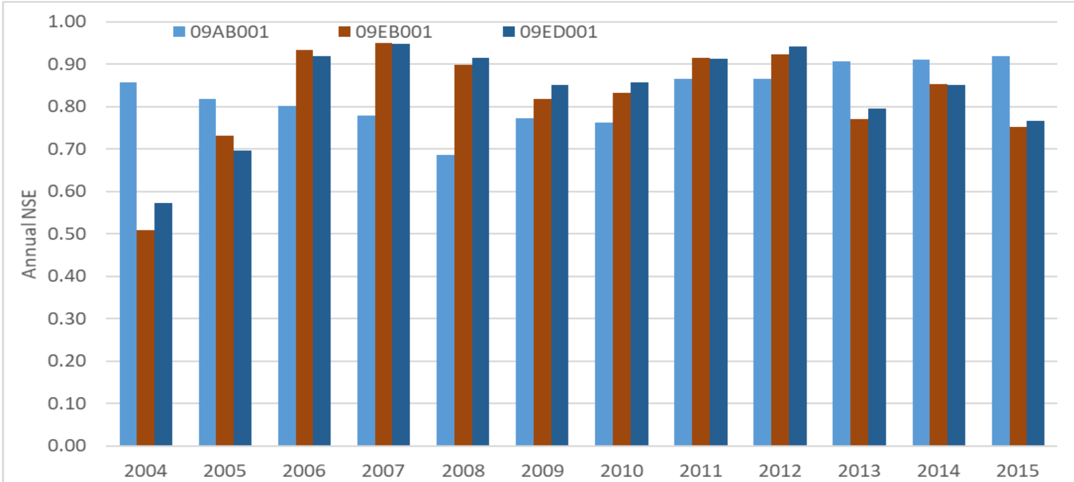
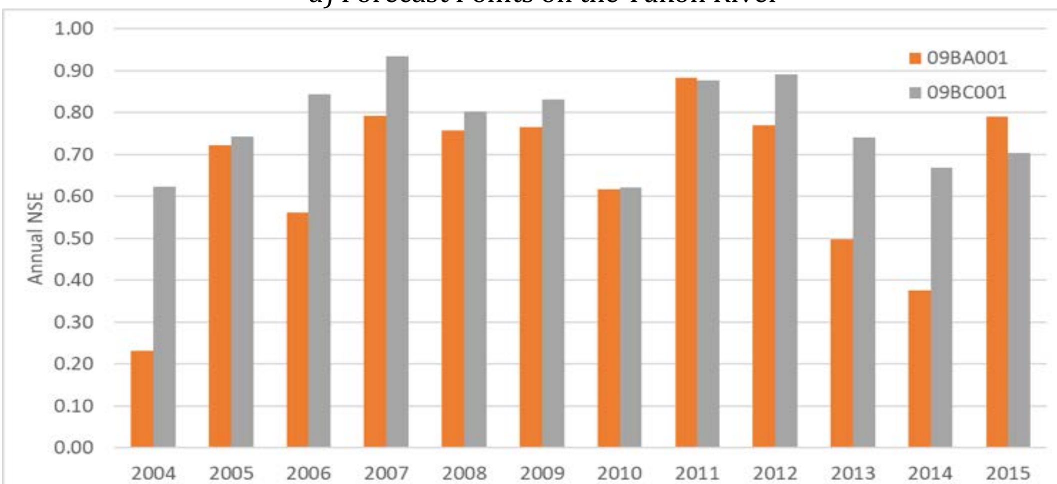


Figure 14: Hydrographs at all forecast points in the Main Yukon for the 2004-2015 period

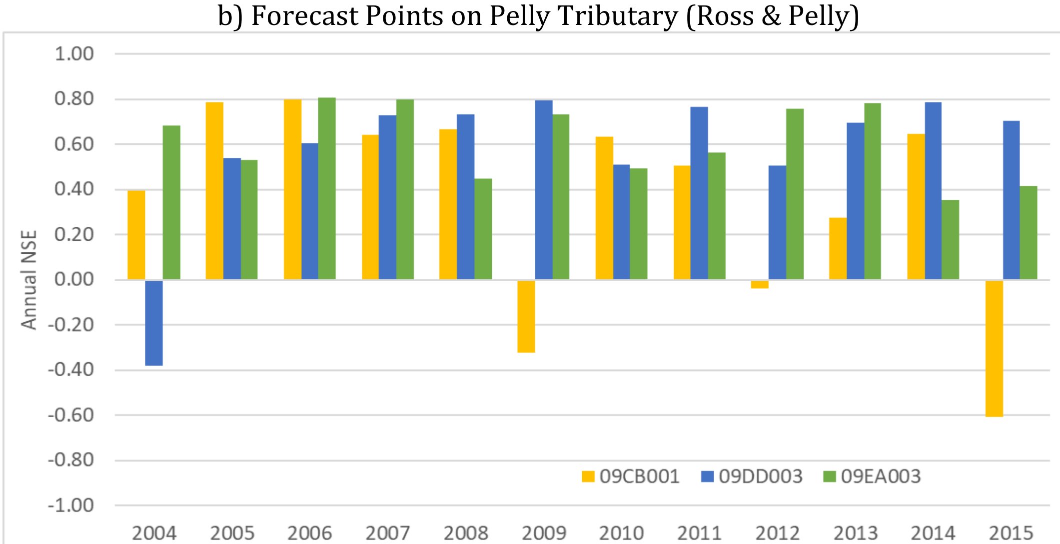
From these figures and tables, we can see that the model performance is very satisfactory (NSE > 0.70) for forecast points on the main Yukon for most years and aspects, especially at Whitehorse. The system above Whitehorse, however, is slow responding due to the existence of inter-connected lakes. The inclusion of those lakes in the model, and the proper parameterization of glacier albedos helped attain such high performance at Whitehorse which is also reflected as satisfactory at Dawson and Eagle and having relatively stable values for NSE for those stations across the years (Figure 15a). Performance at the forecast point on the Ross (09BA001) is the fine but variable from one year to another (Figure 15b). The impact of that is alleviated to some extent at the outlet of the Pelly (09BC001) which is satisfactory for most years. The performance of the Klondike (09EA003) is generally satisfactory (NSE > 0.5) but drops in some years. The performance of the Upper White (09CB001) is also generally fine but the peaks are over-estimated in a few years (e.g. 2015) leading to drops in performance in several years (e.g. 2015). The performance of the Stewart (09DD003) is generally fine but has large over-estimation in 2004 which could be possibly be related to initialization (Figure 15c).



a) Forecast Points on the Yukon River

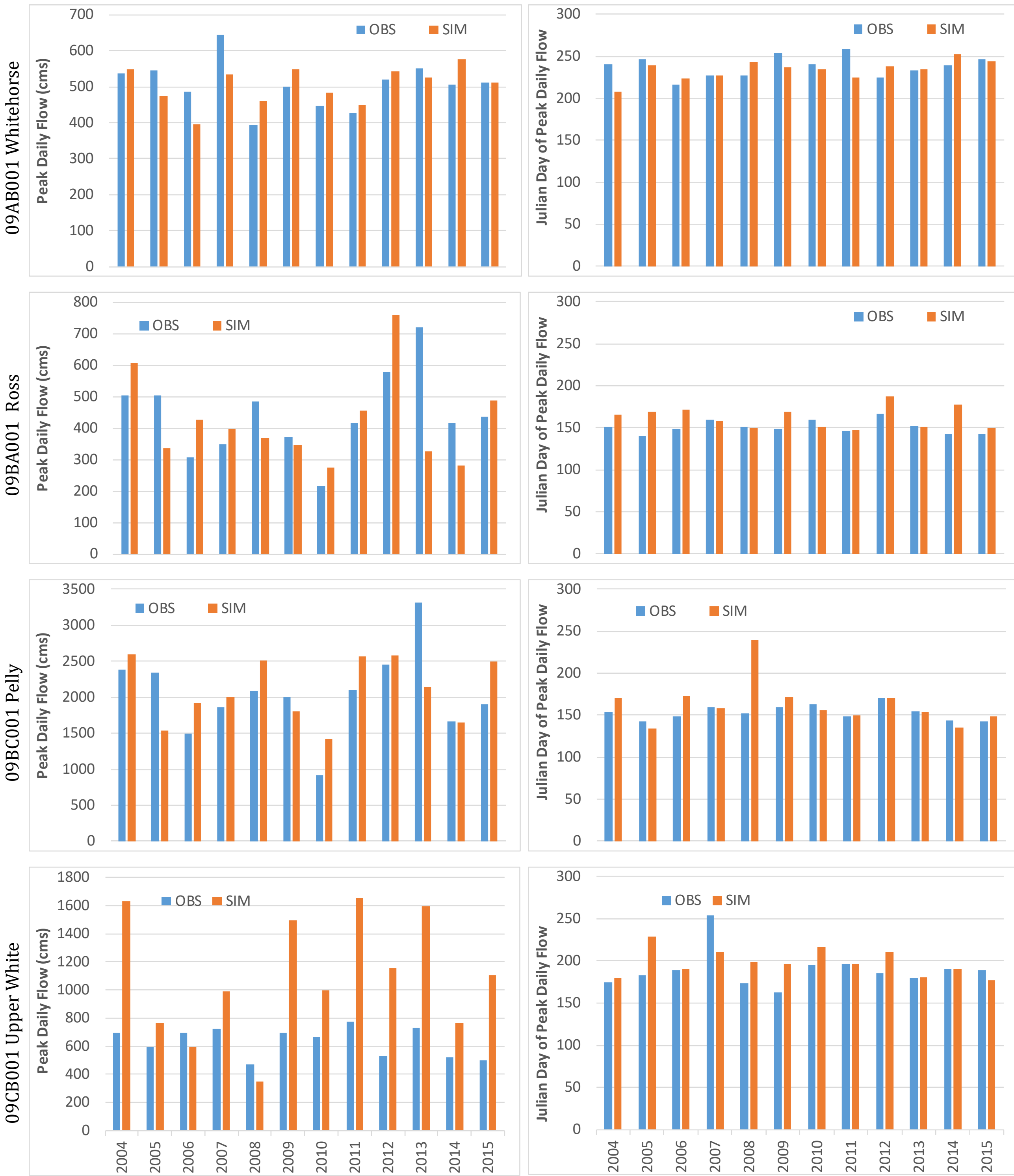


b) Forecast Points on Pelly Tributary (Ross & Pelly)



c) Forecast Points on Upper White, Stewart & Klondike

Figure 15: Performance by year at all forecast Points


09AB001 Whitehorse
09BA001 Ross
09BC001 Pelly
09CB001 Upper White
Peak Daily Flow (cms)
Julian Day of Peak Daily Flow
OBS
SIM
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015

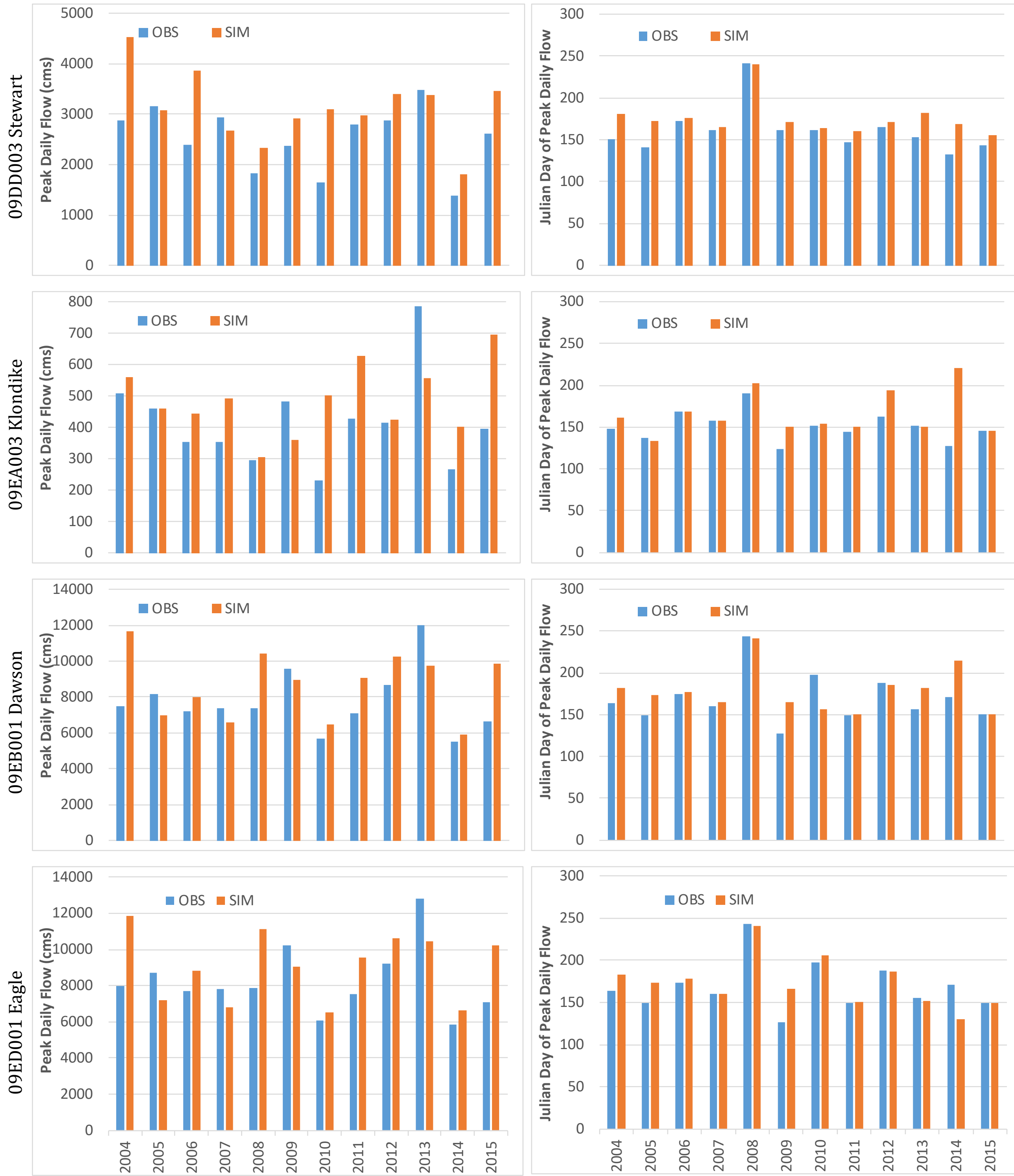


Figure 16: Performance of Hydrological Model for Daily Peak Values and Timing

As the purpose of this modelling exercise is providing forecasts, daily peak flow and their day of occurrence were compared to observations for all forecast points in Figure 16. The performance is generally reasonable in terms of timing, especially for the Main Yukon points (Eagle, Dawson and Whitehorse) and satisfactory for Ross, Pelly and Klondike but peak values are generally over-estimated for the Upper White and Stewart tributaries which gets reflected on the Main Yukon at Dawson and Eagle. Although models can be calibrated individually for each sub-basin at this scale, this is left to the finer scale as it provides better opportunities (see the following section). Improved tributary inflows can be ingested into the main Yukon setup to improve the forecasts at Dawson and Eagle as desired.

Variable performance from one year to another is possibly related to the quality of precipitation. The Main Yukon basin is unevenly covered by meteorological gauges (Figure 17) with some of the considered sub-basins (e.g. upper White) without a single gauge while others have no or few stations in their upper reaches (e.g. Stewart, Ross). This means, CaPA does not contain any ground information to correct the GEM precipitation fields. The incorporation of additional gauges from the Yukon territorial government, Alaska state government, and other sources could improve the precipitation input leading to improved hydrological performance.

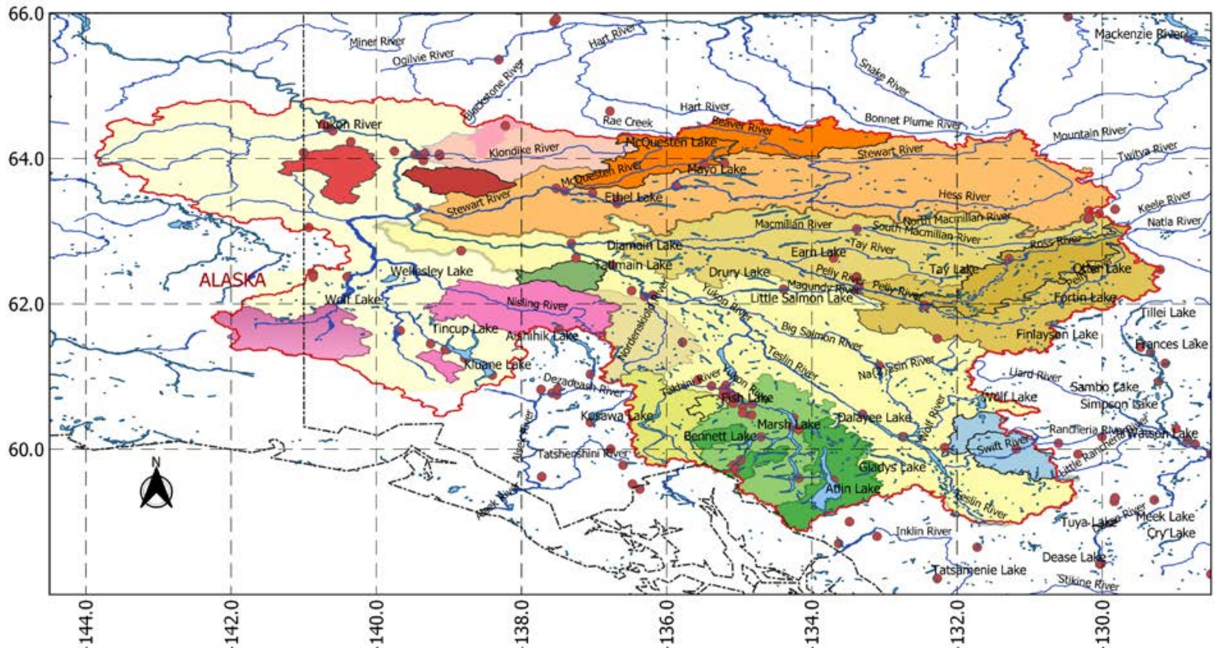


Figure 17: Distribution of Canadian meteorological stations (red dots) in the Main Yukon River Basin

5. Methodology: Higher Resolution MESH Models for Five Sub-basins

The purpose of this chapter is to consider the benefits of higher resolution hydrological models for five sub-basins of the Yukon River Basin. These sub-basins presented considerable challenges in operational river forecasting for the Main Yukon setups or were outside of the basin area but still of interest. They are the Porcupine River near the International Boundary and the Klondike, Stewart, Pelly and White Rivers at their mouths (Figure 18). Separate maps also depict the hydrological network and neighbouring towns of each sub-basin in Figure 19, Figure 20, and Figure 21. Particular modeling difficulties stem from the presence of large wetland areas such as in the lowlands of Old Crow River basin, numerous lakes of different sizes and glacierized drainage areas such as the headwaters of White River in the Wrangell-St Elias Mountains. An initial computational analysis suggested that using a MESH grid resolution of 1/16th degree latitude/longitude (0.0625° or 3.75') would be suitable for resolving the river network flow directions and would be feasible to implement. This higher resolution implementation of MESH was felt to be suitable for simulation of smaller river sub-basins.

Similar to the Main Yukon setup, topographic data are extracted from the conditioned MERIT DEM dataset at 3-arc-seconds resolution (Yamazaki et al., 2017). As for land cover, the 2010 map at 7.5-arc-second spatial resolution, from North American Land Change Monitoring System (NALCMS) was used here. This dataset is made available by the Commission for Environmental Cooperation (CEC) between Canada, Mexico, and the United States. It accommodates nineteen land cover classes defined by the Land Cover Classification System (LCCS) standard developed by the Food and Agriculture Organization (FAO) of United Nations. For the study domains here, NALCMS land cover was reclassified into 8 classes to be considered as GRUs in MESH: Needleleaf forest, Broadleaf forest, Mixed forest, Shrubs/grass, Alpine, Wetland, Water and Glacier. The water courses and waterbodies are obtained from geospatial CanVec data series published by Natural Resources Canada. CanVec offers the most current, accurate, and consistent river/lake network and it complies with international geomatics standards. This GIS information helped with the support of the DEM in digitizing the boundaries of all sub-basins.

The National Research Council Canada (NRCC)'s Green Kenue hydrological analysis and visualization software (https://www.nrc-cnrc.gc.ca/eng/solutions/advisory/green_kenue_ index.html) was used to map topography and land cover onto the discretized domain, and to create flow directions, drainage areas and drainage densities. Flow directions were quality controlled and corrected. Due to code limitations, soil depth was input as a constant of 4 metres over all domains. Meanwhile, a high resolution soil discretization was selected as it additionally helped stabilize MESH runs by preventing sporadic crashes. That is, eight layers of thicknesses from top to bottom 10, 10, 20, 20, 40, 100, 100 and 100 m were chosen.

Parameters were selected by manual calibration for each basin model setup with a focus on fitting spring runoff hydrographs and achieving acceptable peak flow prediction capability. While only vegetation parameters were fixed to their physical values in CLASS, other parameters were allowed to vary taking into account the presence of water bodies for which there is sparse information and so parameter uncertainty. Hydrometric gauges whose data was used for comparison with simulated flows are listed in Table 10. Although manual calibration is tedious and slow, it generally prompts an enhanced understanding of the effect of parameters on model solutions and helps build an alternative formalism to automatic optimization with its local minima traps.

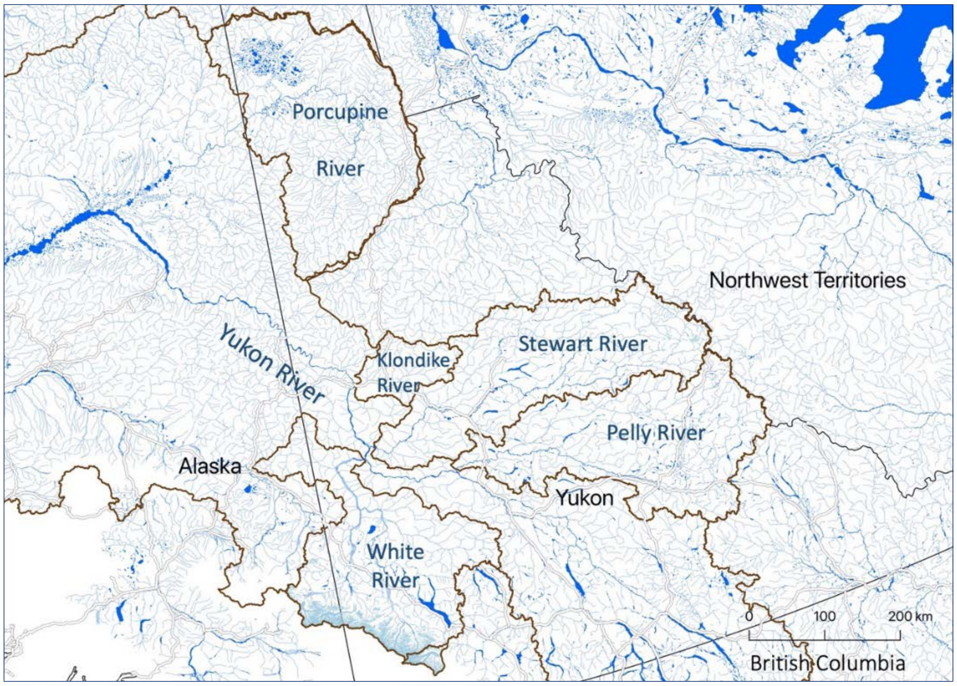


Figure 18: Location of five Yukon River sub-basins modelled at higher resolution

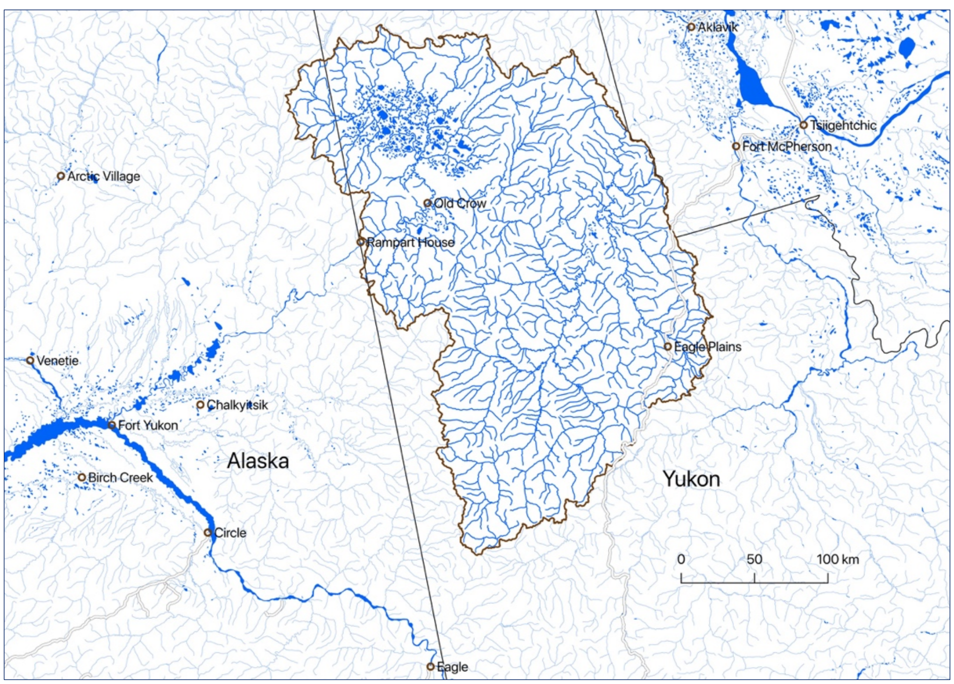


Figure 19: Hydrological network of the Porcupine River Basin

Figure 20: Hydrological network of the Klondike, Stewart and Pelly River Basins

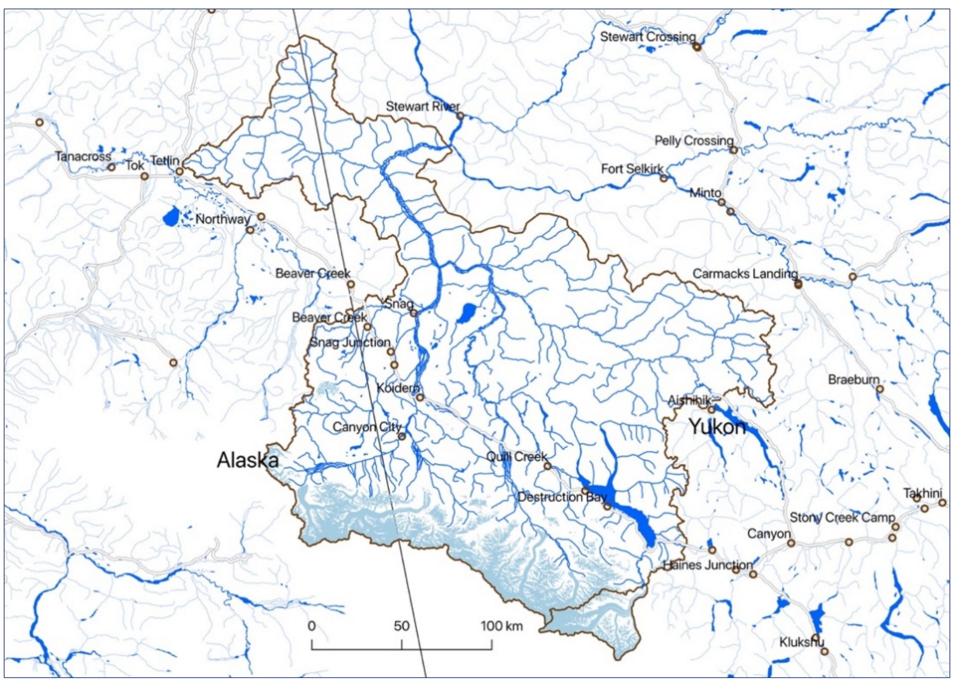


Figure 21: Hydrological network of the White River Basin

Table 10: Hydrometric gauges used in the high resolution modelling of the five sub-basins

Sub-basin	Hydrometric Station	Station Code	Longitude Latitude	Drainage Area	Period of Record
Porcupine River	Porcupine R. near International Boundary	09FD002	140° 53' 28" 67° 25' 27"	58,900	1987-present
	Old Crow R. near the Mouth	09FC001	139° 41' 47" 67° 38' 04"	13,900	1976-present
Klondike River	Klondike R. above Bonanza Cr.	09EA003	139° 24' 28" 64° 02' 34"	7,810	1965-present
	North Klondike R. near the Mouth	09EA004	138° 35' 46" 64° 00' 07"	1,090	1974-present
Stewart River	Stewart R. at the Mouth	09DD003	139° 15' 16" 63° 16' 56"	51,000	1951-present
	Hess R. above Emerald Cr.	09DA001	131° 29' 27" 63° 20' 00"	4,840	1976-1996 2015-present
	Beaver R. below Matson Cr.	09DB001	134° 08' 21" 64° 00' 54"	4,770	1995-present
	McQuesten R. near the Mouth	09DD004	137° 16' 10" 63° 36' 40"	4,750	1979-present
Pelly River	Pelly R. at Pelly Crossing	09BC001	136° 34' 50" 62° 49' 47"	48,900	1951-present
	Pelly R. below Vangorda Cr.	09BC004	133° 22' 40" 62° 13' 14"	21,900	1970-present
	Ross R. at Ross R.	09BA001	132° 24' 25" 61° 59' 19"	7,310	1958-present
	Pelly R. below Fortin Cr.	09BA002	130° 36' 10" 62° 01' 50"	5,020	1986-94 2012-16
White River	White R. at km 1881.6 Alaska Highway	09CB001	140° 33' 31" 61° 59' 17"	6,230	1974-present
	Duke R. near the Mouth	09CA004	139° 10' 04" 61° 20' 45"	654	1981-present
	Nisling R. below Onion Cr.	09CA006	139° 02' 33" 62° 12' 17"	7,910	1995-present

Meanwhile, the design of these model setups allowed for further use of discharge measurements inside sub-basins and calibration improvements depending on the forecasting points of interest. For sharing a better understanding and visualization of river flow trajectories and confluences, several sub sub-basins were digitized (Figure 22, Figure 29, Figure 34, Figure 38, and Figure 47), which helped in the construction of water numerical paths as a basis for modeling precision. Discretized drainage areas are also illustrated in Figure 23, Figure 30, Figure 35, Figure 39, and Figure 48. Table 11 lists these sub-divisions for each of the 5 Yukon Sub-basins considered with additional details for the Old Crow tributary of the Porcupine River basin.

There's a land where the mountains are nameless
And the rivers all run God knows where
(from The Spell of the Yukon by Robert W. Service)

Table 11: Delineated Sub sub-basins of Main Sub-basins Considered for High Resolution Modelling

Sub-basins of Porcupine River:	Sub-basins of Klondike River:	Sub-basins of Stewart River:
1. Old Crow River: a. Black Fox Creek b. Johnson Creek (North) c. Schaeffer Creek (North) d. Surprise Creek e. Thomas Creek f. Timber Creek 2. Little Bell River 3. Lower Bell River 4. Upper Bell River 5. Berry Creek 6. Big Joe Creek 7. Bluefish River 8. Burnthill Creek 9. Cody Creek 10. Caribou Bar Creek 11. Chance Creek 12. David Lord Creek 13. Driftwood River 14. Eagle River 15. Ellen Creek 16. Fish Creek 17. Fishing Branch River 18. Johnson Creek (East) 19. Johnson Creek (West) 20. La Chute River 21. Miner River 22. Nukon Creek 23. Pine Creek 24. Rock River 25. Schaeffer Creek (South) 26. Waters River 27. Whitestone River	1. Allgold Creek 2. Aussie Creek 3. Bonanza Creek 4. Brewery Creek 5. Coal Creek 6. Davidson Creek 7. Flat Creek 8. Gates Creek 9. Gilcher Creek 10. Lee Creek 11. Rabbit Creek 12. Rock Creek 13. Hamilton Creek 14. Hunker Creek 15. Lepine Creek 16. Little South Klondike River 17. North Klondike River Sub-basins of Pelly River: 1. Big Campbell Creek 2. Earn River 3. Hoole River 4. Kalzas River 5. Lapie River 6. MacMillan River 7. North MacMillan River 8. South MacMillan River 9. Mica Creek 10. Needlerock Creek 11. Ross River 12. Tay River 13. Tummel River 14. Willow Creek 15. Woodside River	1. Beaver River 2. Black Hills Creek 3. Clear Creek 4. Crooked Creek 5. Grand Valley Creek 6. Hess River 7. Keno Ladue River 8. Lake Creek 9. Lansing River 10. Mayo Lake 11. McQuesten River 12. Nadaleen River 13. Nogold Creek 14. Pleasant Creek 15. Rogue River 16. Walhalla Creek Sub-basins of White River: 1. Donjek River 2. Generc River 3. Kluane River 4. Ladue River 5. Nisling River 6. Snag Creek

5.1 Porcupine River

The wetlands surrounding the main stem of Old Crow River are covered by more than 2000 lakes of dissimilar sizes and shapes and constitute an extraordinary and poorly drained water-land system that is very challenging to model with any hydrological land surface scheme. Therefore, the initial modelling effort here focused on trying to reproduce peak flows. Whilst results are encouraging for seven years (2005, 2006, 2007, 2010, 2011, 2014 and 2016), the simulations in the other years show an underestimation except in 2008 (see Figure 24 and Figure 25). The calculated NSE value of 0.57 over the whole period (2005-2017) here (Table 12) reflects the adequacy of this pioneering distributed hydrological modeling of Old Crow River in predicting high flows and flood events. Model uncertainty was amplified by the inability of GEM-CaPA precipitation to capture realistic winter accumulations throughout the basin because of the scarcity of assimilated stations in the region and other factors. Indeed, analysis of correspondence between October to April accumulated CaPA precipitation and May 1st snow survey shows no trend. Improving the model will require advanced sets of hydrometeorological and hydrometric data and an improved understanding of permafrost lake-wetland complexes that would support water routing across the poorly drained region. On the other hand, as displayed in Figure 26, there is a good correlation between observed peak flows at Old Crow and May 1st snow survey SWE at the Old Crow site 09FD-SC01, which seems to be very useful in informing high peaks in exceptionally wet years such as 2015. 2011 was also a high flow year for the Old Crow and an available snow survey SWE of 153 mm in April 1st is in agreement with the key forecasting graph.

Table 12: Evaluation metrics for five sub-basins simulations (2005-2017). NSE (Nash-Sutcliffe Efficiency), PBIAS (Percent bias), NSElog (NSE of log-transformed values)

Station	NSE	PBIAS (%)	NSElog
Old Crow River near the Mouth	0.57	-11.41	-0.05
Porcupine River near International Boundary	0.55	-18.59	-0.88
Porcupine River near International Boundary compared to Porcupine upstream Old Crow	0.67	-37.89	-1.52
Porcupine River near International Boundary compared to Porcupine downstream Old Crow	0.63	-23.27	-1.20
Klondike R. above Bonanza Cr.	0.72	-19.71	-0.53
Stewart R. at the Mouth	0.77	-15.48	0.802
Beaver R. below Matson Cr.	0.68	-16.71	0.55
Pelly R. at Pelly Crossing	0.74	-19.64	0.74
Pelly R. below van Gordra Cr.	0.75	-17.93	0.78
Ross R. at Ross R.	0.75	-12.79	0.805
White R. at km 1881.6 Alaska Highway	0.55	-27.83	-1.98

Figure 27 shows simulation results for the Porcupine River while Figure 28 focuses on peak flows. There is an overestimation of simulated flows near the International Boundary (NSE=0.55), thus rather, the plots here compare observed flows to simulated ones upstream (NSE=0.67) and downstream (NSE=0.63) of the confluence with Old Crow River. Again, the model solutions here have to be considered with caution and further hydrometric and modeling investigations should be sought for this forecasting point and all along the Porcupine River. For the two years with much higher flows, the upstream output tracked better the 2011 peak flow in fast melt conditions, when the downstream output reproduced the 2015 hydrograph in slow melt conditions.

5.2 Klondike River

The MESH hydrological simulation for the Klondike River basin yielded modelled streamflows that were very consistent with observed ones as shown by an overall NSE of 0.72 (Figure 31 and Table 12). Almost all peaks were predicted correctly but not necessarily timely. While the flow hydrograph and peak of flood year 2009 were very well resolved, the model substantially underestimated the peak in flood year 2013 by 166 m^3/s. Conversely, the model overestimated the peak in the dry year 2010 by 176 m^3/s (Figure 32). These two large discrepancies in the results, accompanied with difficulties in model calibration, led to the investigation of the consistency of winter CaPA precipitation accumulation with snow survey data. The biases between October to April CaPA precipitation and May 1st snow survey at Midnight Dome site (09EB-SC01) suggest that CaPA precipitation is underestimated and overestimated for 2013 and 2010, respectively. The predicted peaks of 2007 and 2015 were also overestimated by 122 and 132 m^3/s, respectively, but the local snow survey compared more closely to the GEM-CaPA estimates. As plotted in Figure 33, there is a useful correlation between observed peak flows above Bonanza Creek and May 1st snow survey SWE at Midnight Dome site 09EB-SC01, which captures the peak of flood year 2013.

5.3 Stewart River

In this sub-basin, the model results gave very satisfactory evaluation metrics for Stewart River at the Mouth (NSE=0.77 and NSElog=0.802). Figure 36 shows the ability of the model from year to year in reproducing observed flows. Simulated and observed peak flows are also presented in Figure 37. The model overestimated peak flows in 2007 and 2013 and underestimated them in 2010 and 2015. Snow survey data alone only partially predicts peak flows at the mouth, as expected for this large basin. Large rainfall events over the basin around the timing of peak flow can always increase peaks dramatically. Hence, to improve model performance, it is imperative to improve the CaPA precipitation forcing data provided to MESH.

5.4 Pelly River

Model results for the Pelly River sub-basin also showed good flow predictability. NSE values of 0.74, 0.75 and 0.75 were obtained for Pelly River at Pelly Crossing, Pelly River below Vangorda Creek and Ross Creek at Ross Creek respectively. NSElog values were 0.74, 0.78 and 0.805, respectively. Generally, as can be seen in Figures 40 to 43, the model succeeded to track flow hydrograph patterns, yet accuracy in tracking peaks was hindered again by errors in the CaPA precipitation data. Figures 44 to 46 report modelled versus observed peak flow for the three hydrometric stations. The highest errors in simulated peak flows of Pelly River at Pelly Crossing and Ross River are related to the previously diagnosed CaPA precipitation accumulation underestimation in 2013 followed by another underestimation expressed here for the Pelly sub-basin in 2012. The subsequent model underestimation of Pelly River peak flow at Pelly Crossing is 1,450 m^3/s. In contrast, the model reproduced an almost perfect matching of observed peaks in 2006, 2009, 2011 and 2017.

5.5 White River

Modelling the White River sub-basin was the most difficult and least successful. The NSE and NSElog values for results at White River at km 1881.6 Alaska Highway are respectively 0.55 and -1.98. Yearly simulated versus observed flow hydrographs are displayed in Figure 49 and the comparison of peak flows is illustrated in Figure 50. While the times of the response to melt onset and runoff generation are captured by the general flow patterns, the percentage of errors in amplitudes remains unacceptable. The model also showed a weak ability to simulate flows of Duke River at the Mouth and Nisling River below Onion Creek. A number of factors contributed to this model failure; this includes erroneous GEM-CaPA meteorological forcing input over high altitude glacierized areas and the presence of some sizeable moraine lakes with unknown hydrological behaviour and rating curves.

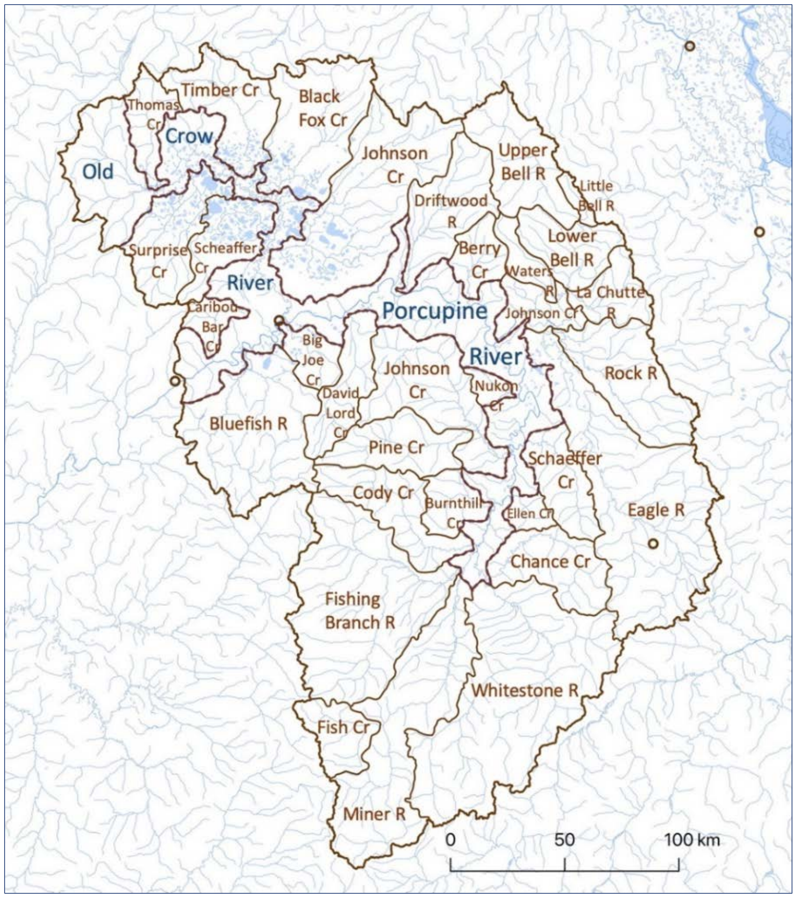


Figure 22: Sub-basins of Old Crow River and Porcupine River

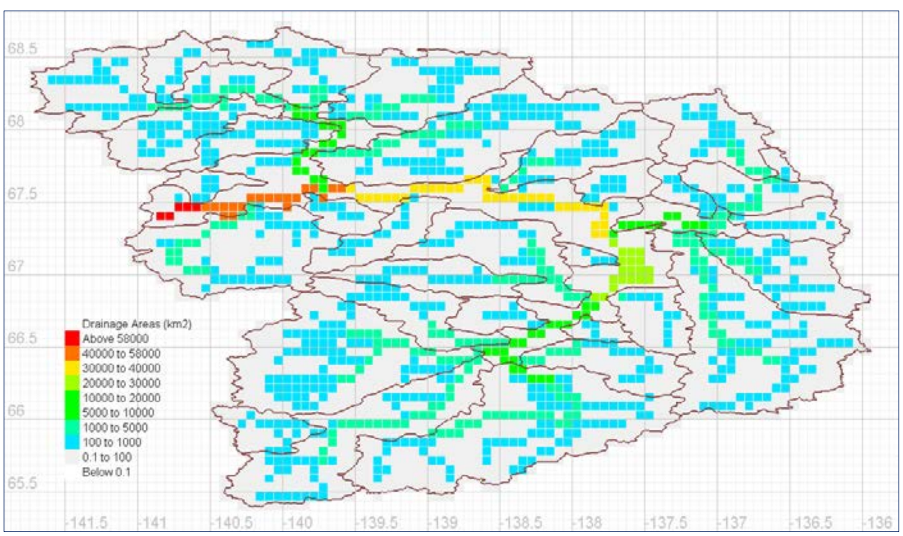


Figure 23: Discretized drainage areas of Old Crow River and Porcupine River at 0.0625° spatial resolution

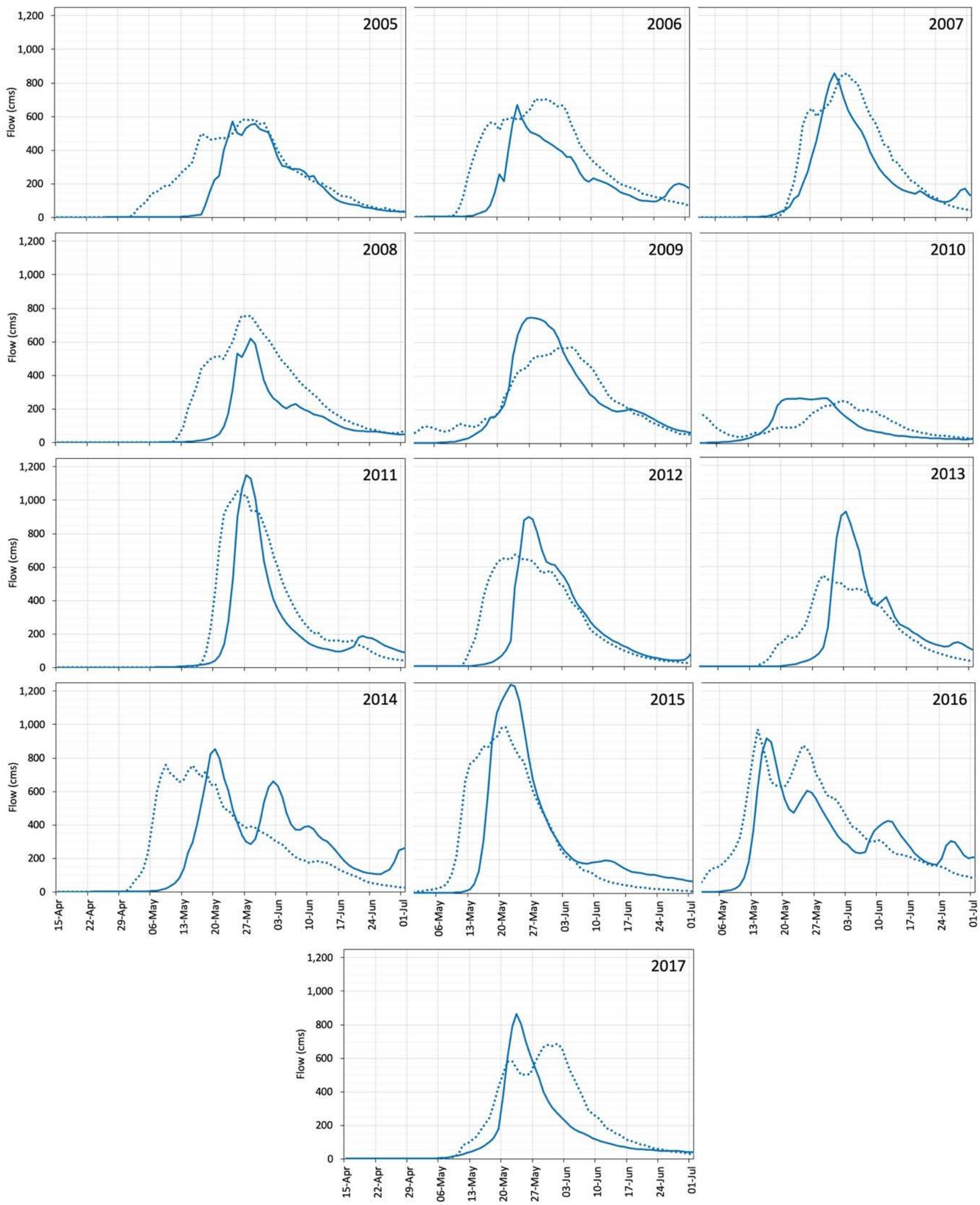


Figure 24: Simulated (dotted line) versus observed (solid line) flows of Old Crow River near the Mouth

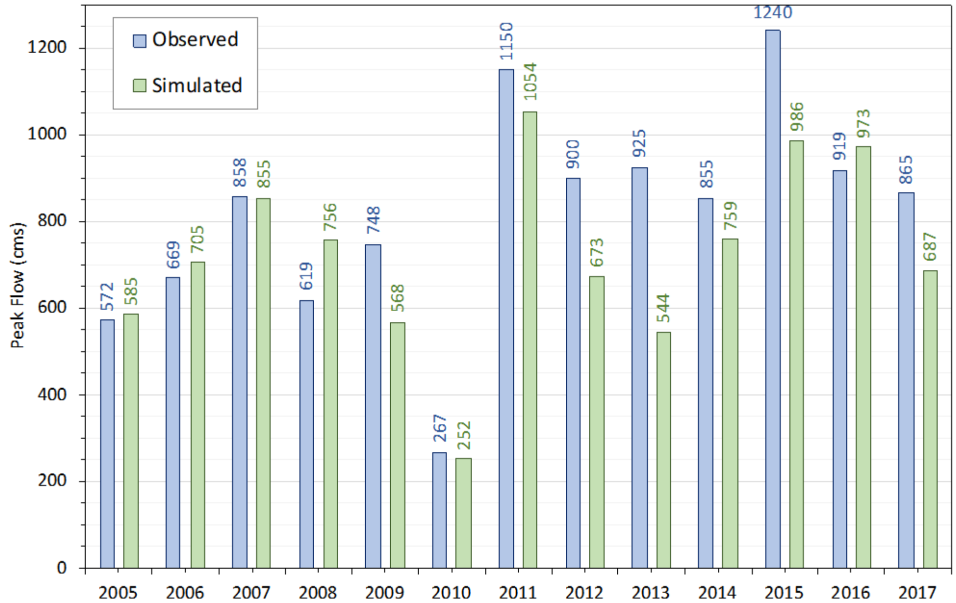


Figure 25: Comparison between observed and simulated peak flows at Old Crow River near the Mouth (09FC001)

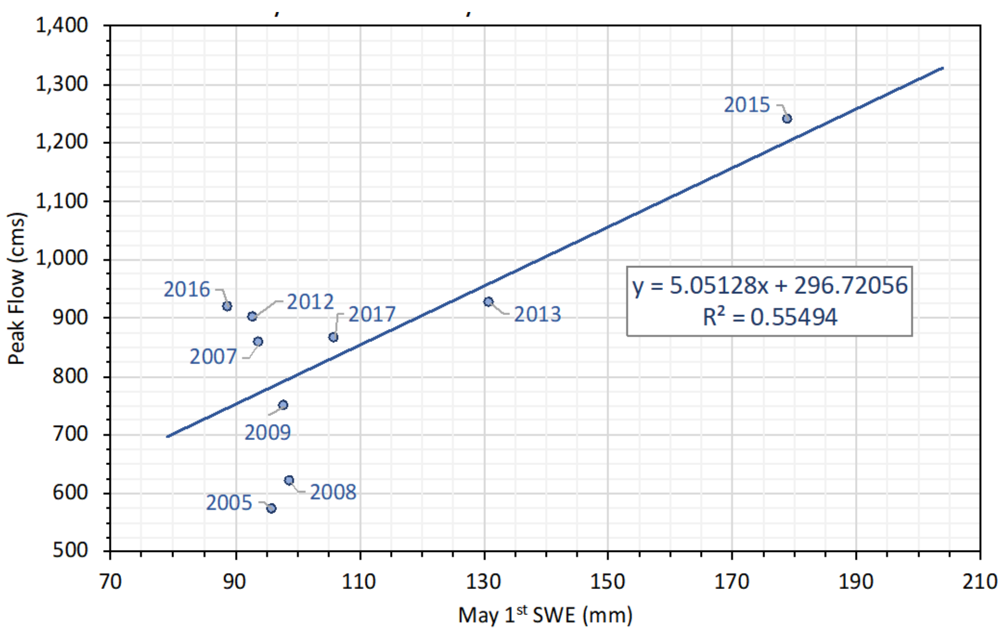


Figure 26: Correlation between spring peak flows of Old Crow River at Mouth (09FC001) and May 1st snow Survey SWE at Old Crow site (09FD-SC01)

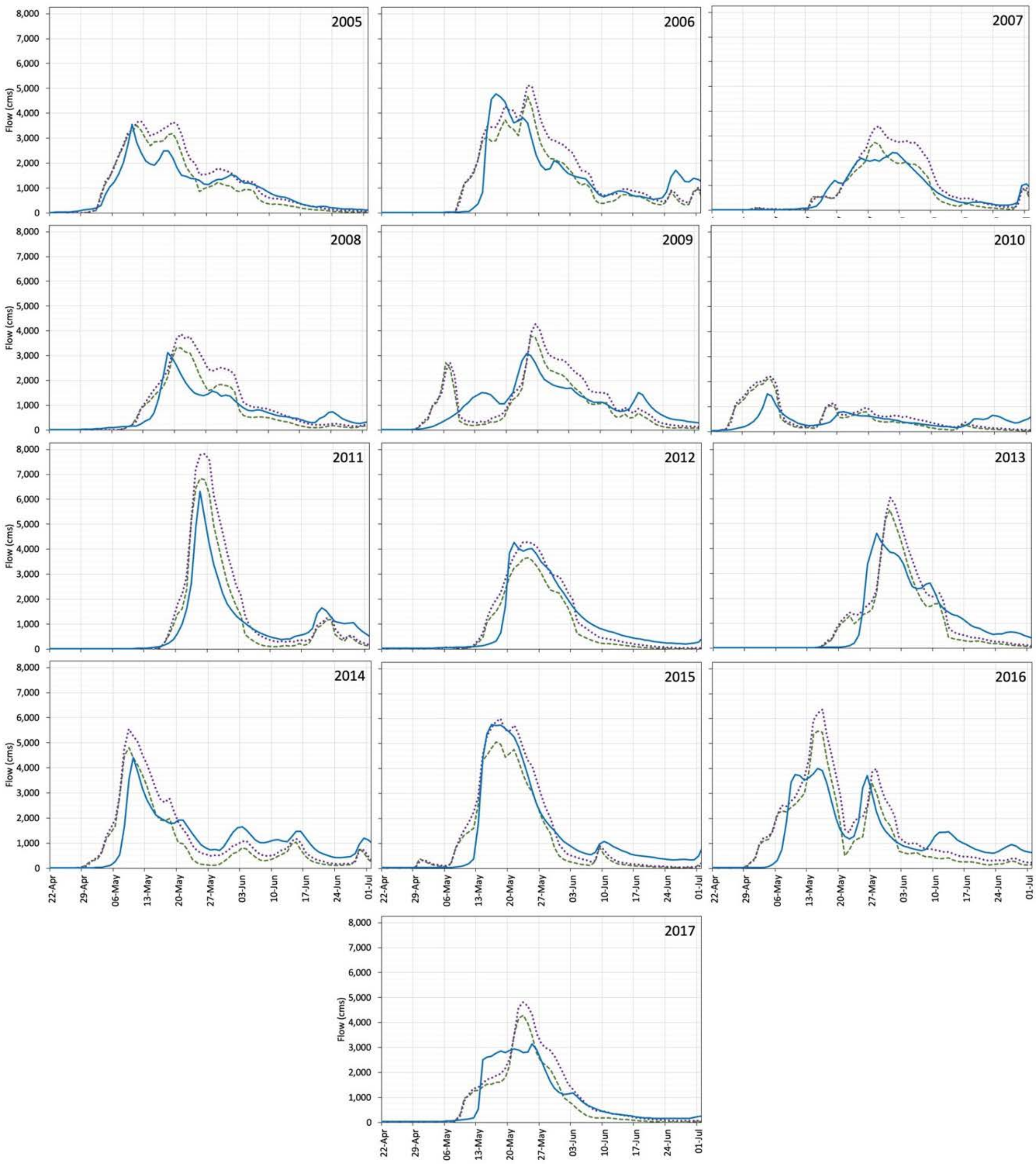


Figure 27: Simulated flows of Porcupine River upstream (dashed line) and downstream (dotted line) the confluence with Old Crow River versus observed flows near International Boundary (solid line)

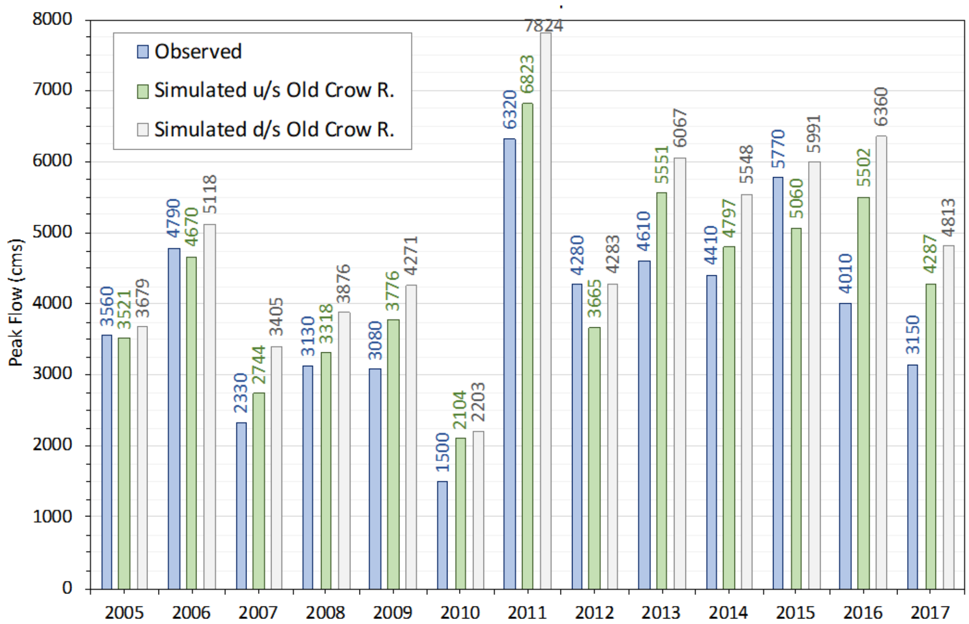


Figure 28: Comparison of observed and simulated peak flows of Porcupine River near International Border (09FD002)

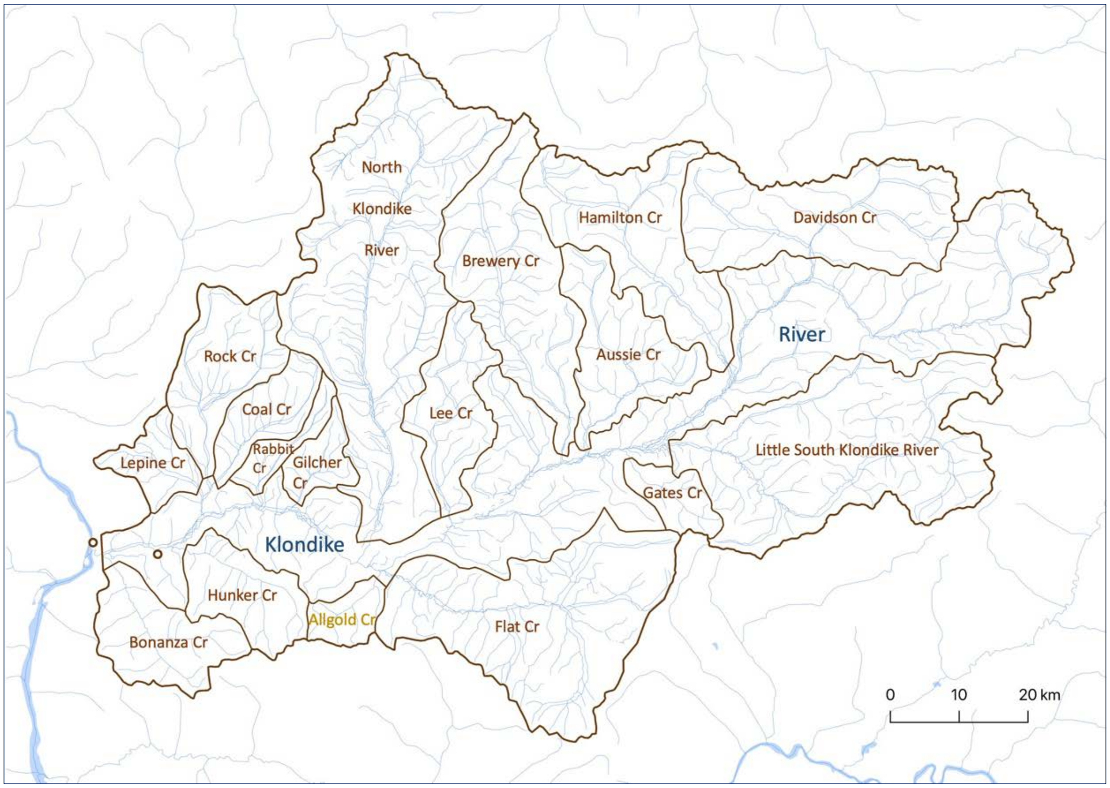


Figure 29: Sub-basins of Klondike River

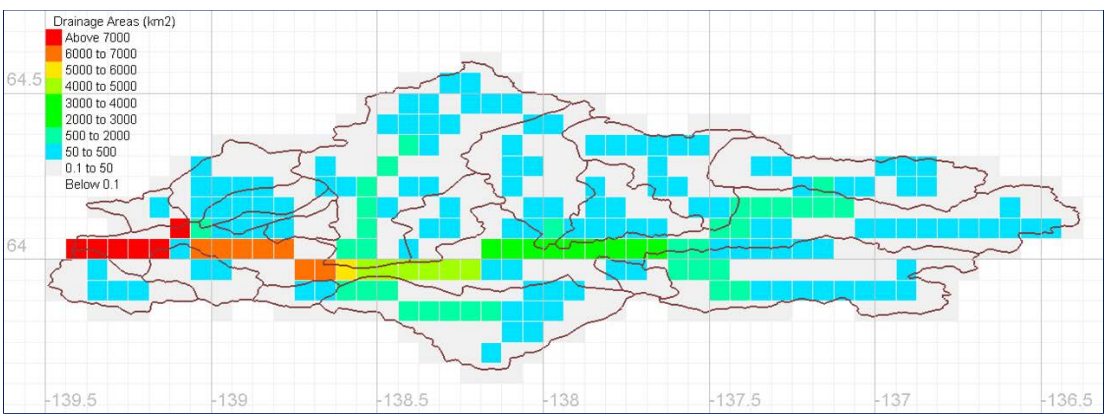


Figure 30: Discretized drainage areas of Klondike River at 0.0625° spatial resolution

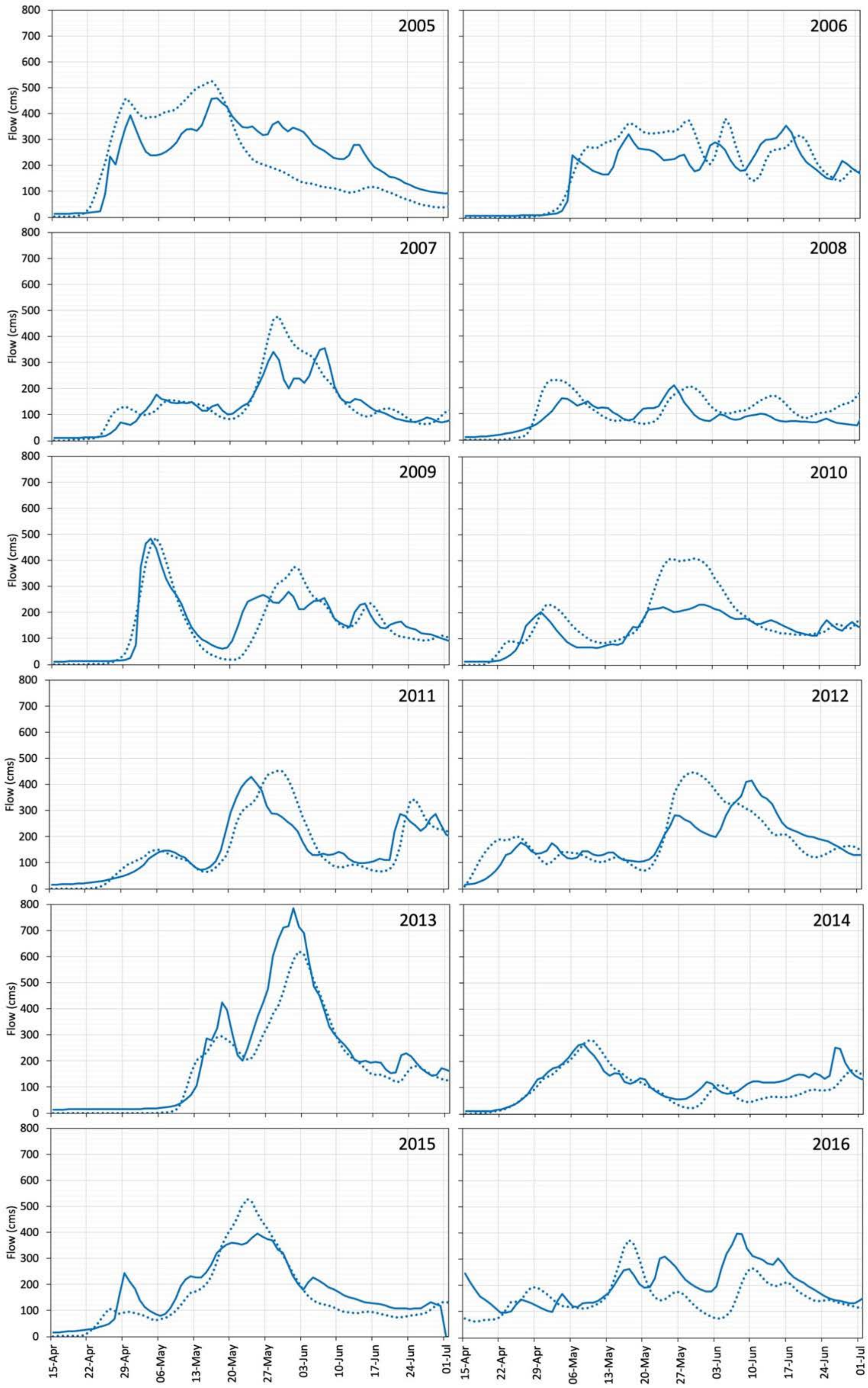


Figure 31: Simulated (dotted line) versus observed (solid line) flows of Klondike River above Bonanza Creek

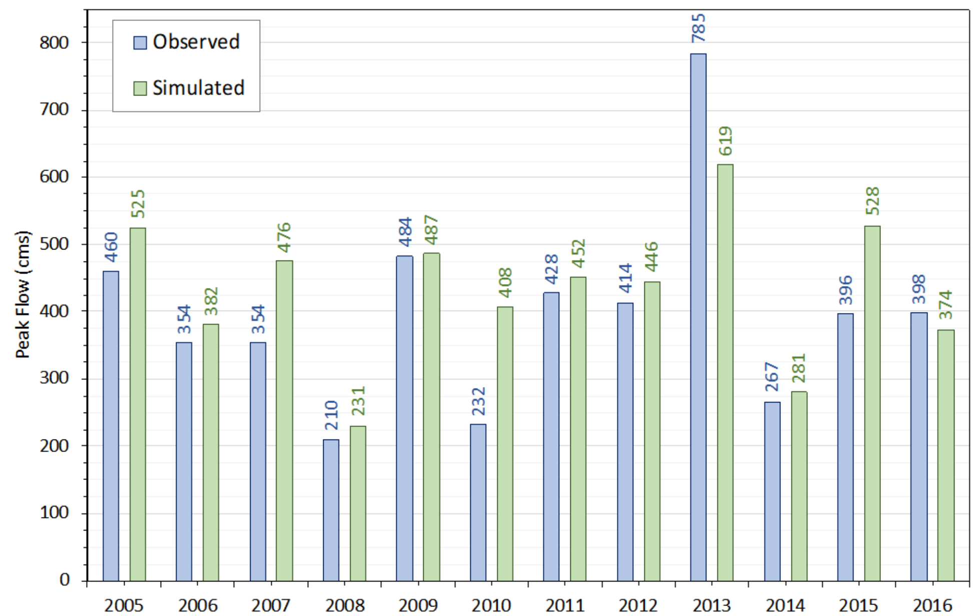


Figure 32: Comparison of observed and simulated peak flows of Klondike River above Bonanza Creek (09EA003)

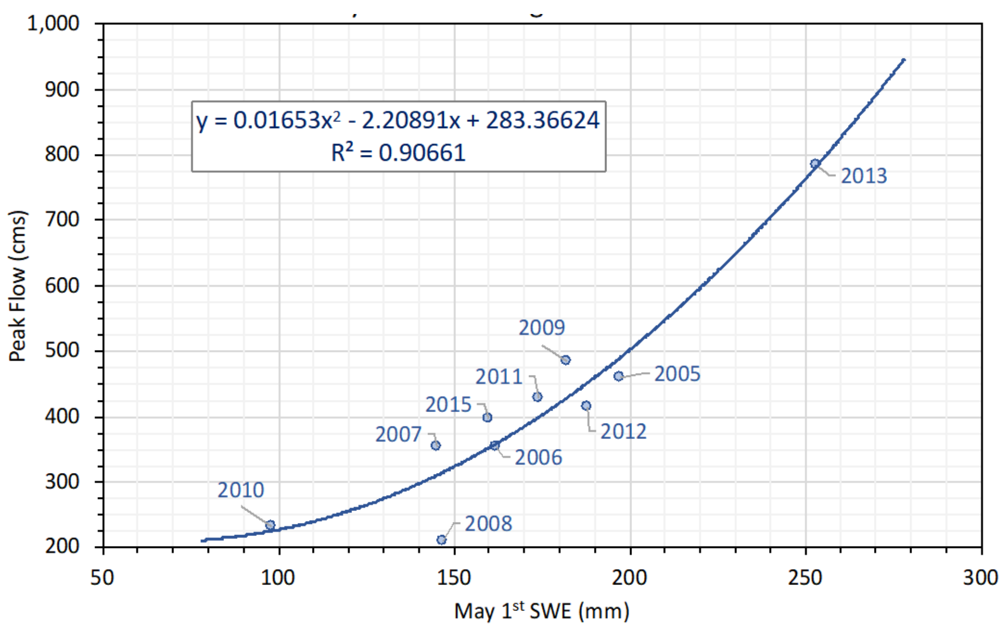


Figure 33: Correlation between spring peak flows of the Klondike River above Bonanza Creek and May 1st snow survey SWE at Midnight Dome site (09EB-SC01)

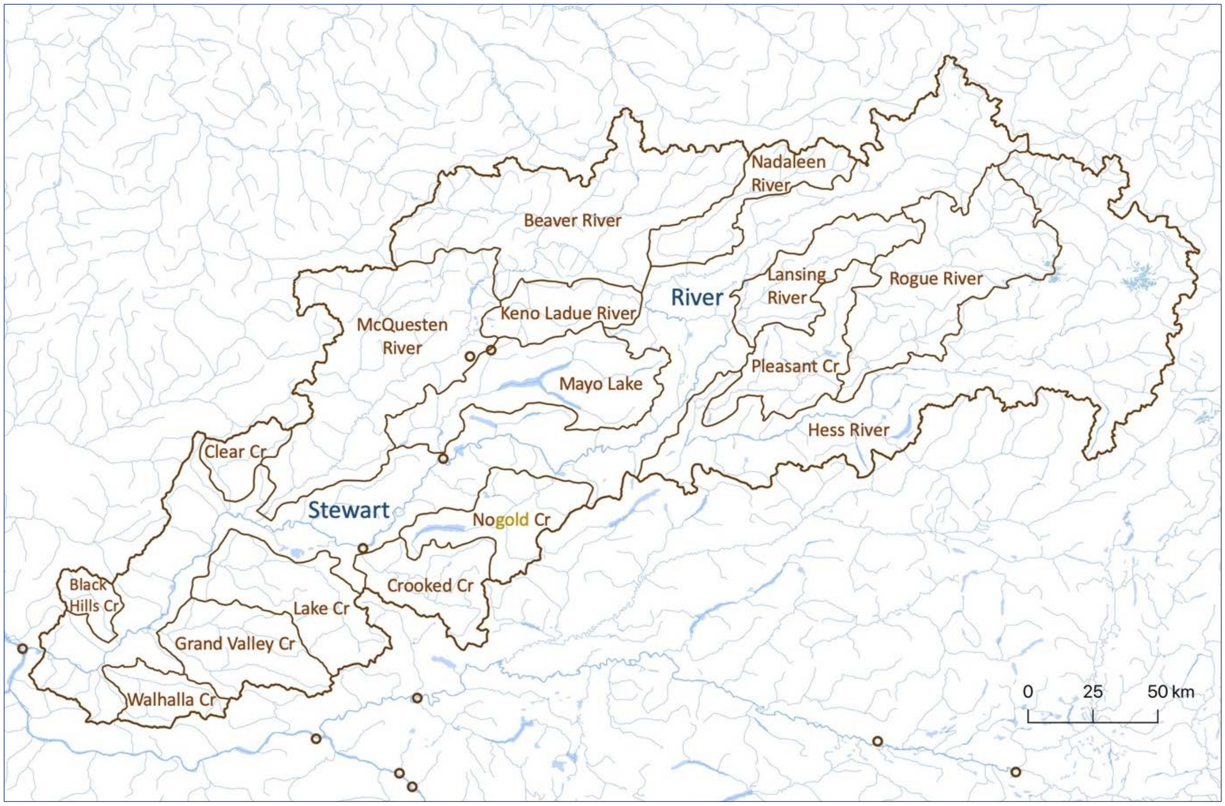


Figure 34: Sub-basins of Stewart River

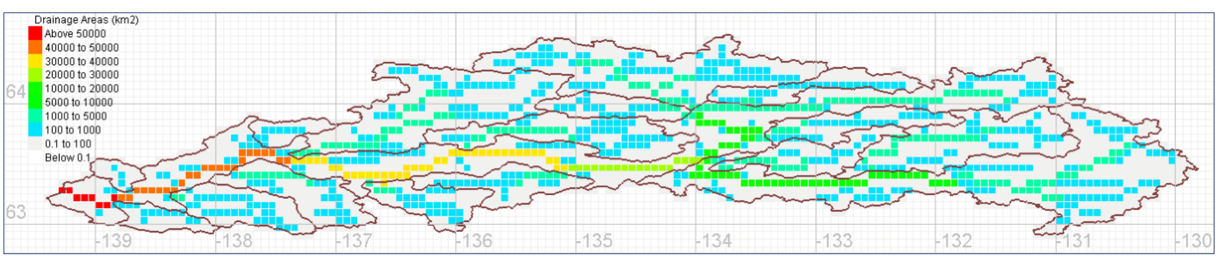


Figure 35: Discretized drainage areas of Stewart River at 0.0625° spatial resolution

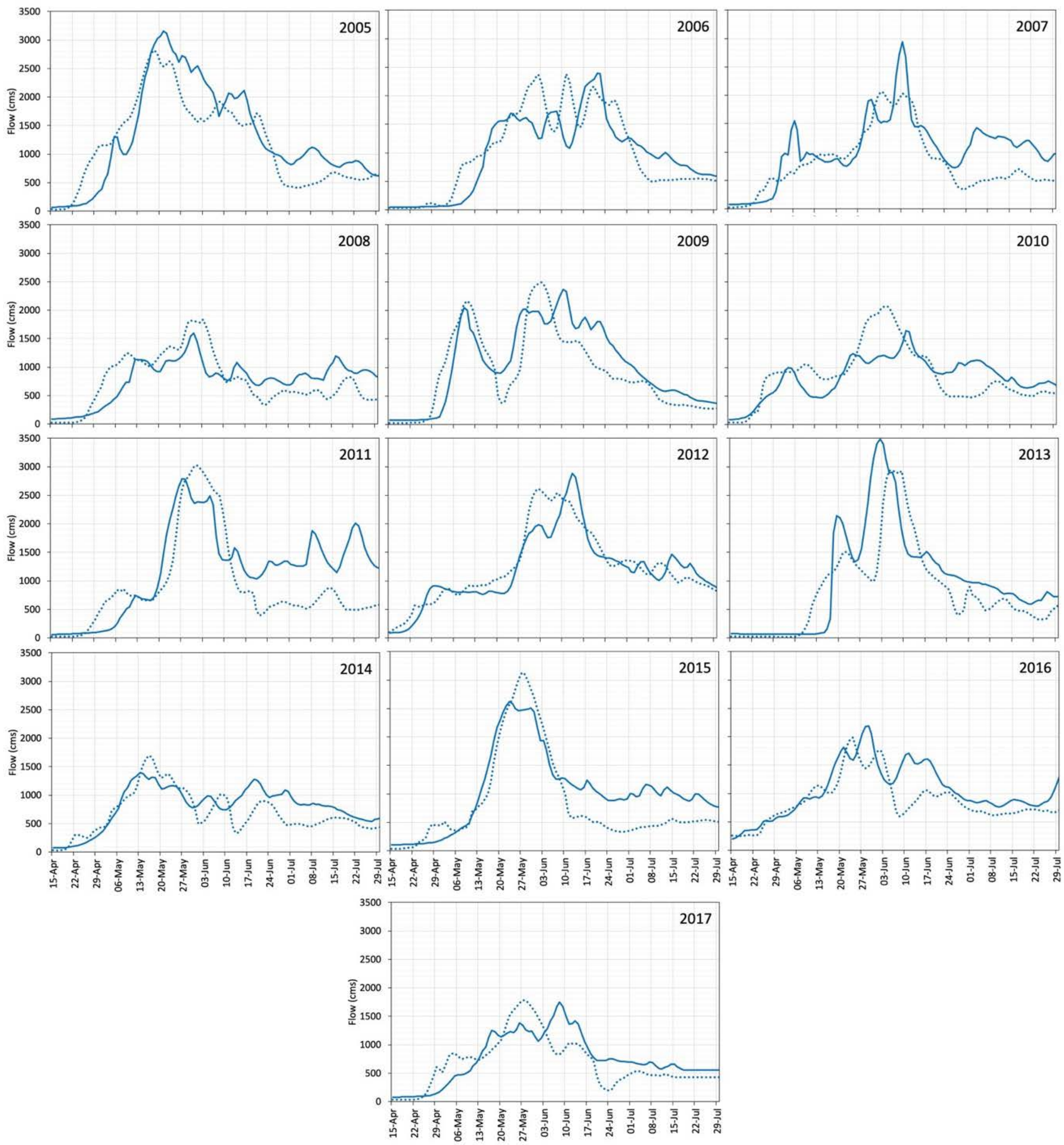


Figure 36: Simulated (dotted line) versus observed (solid line) flows of Stewart River at the Mouth

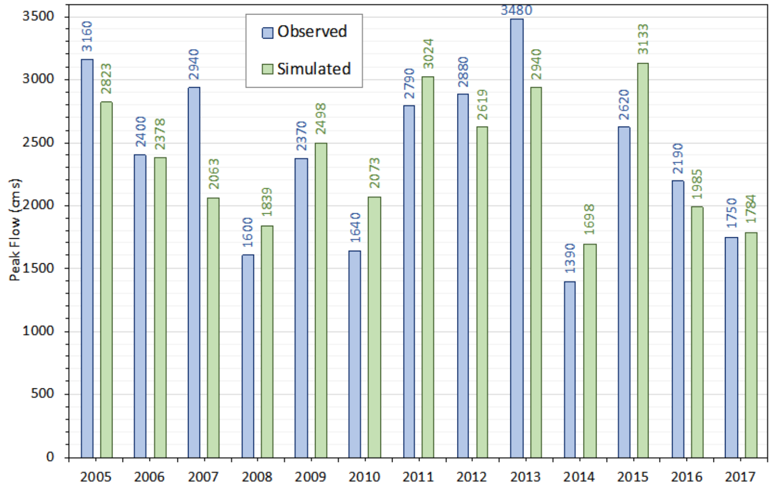


Figure 37: Comparison between observed and simulated peak flows of the Stewart River at the Mouth (09DD003)

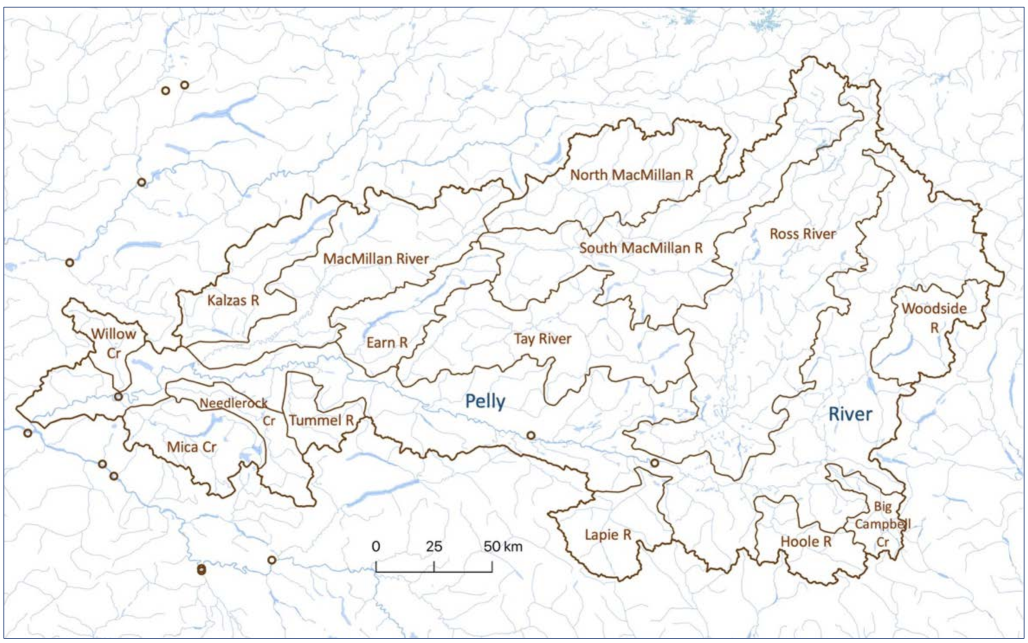


Figure 38: Sub-basins of Pelly River

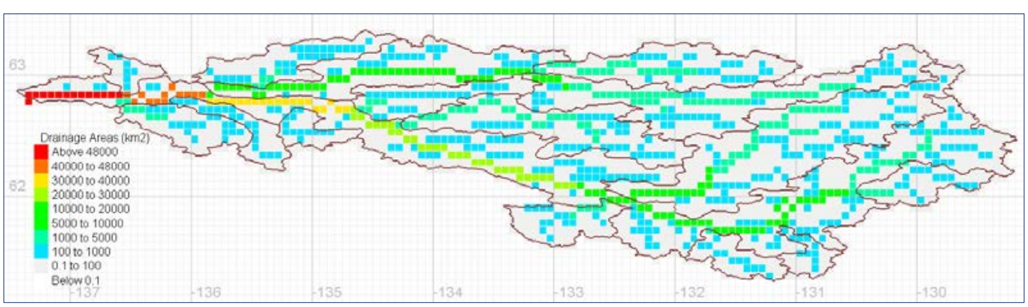


Figure 39: Discretized drainage areas of Pelly River at 0.0625° spatial resolution

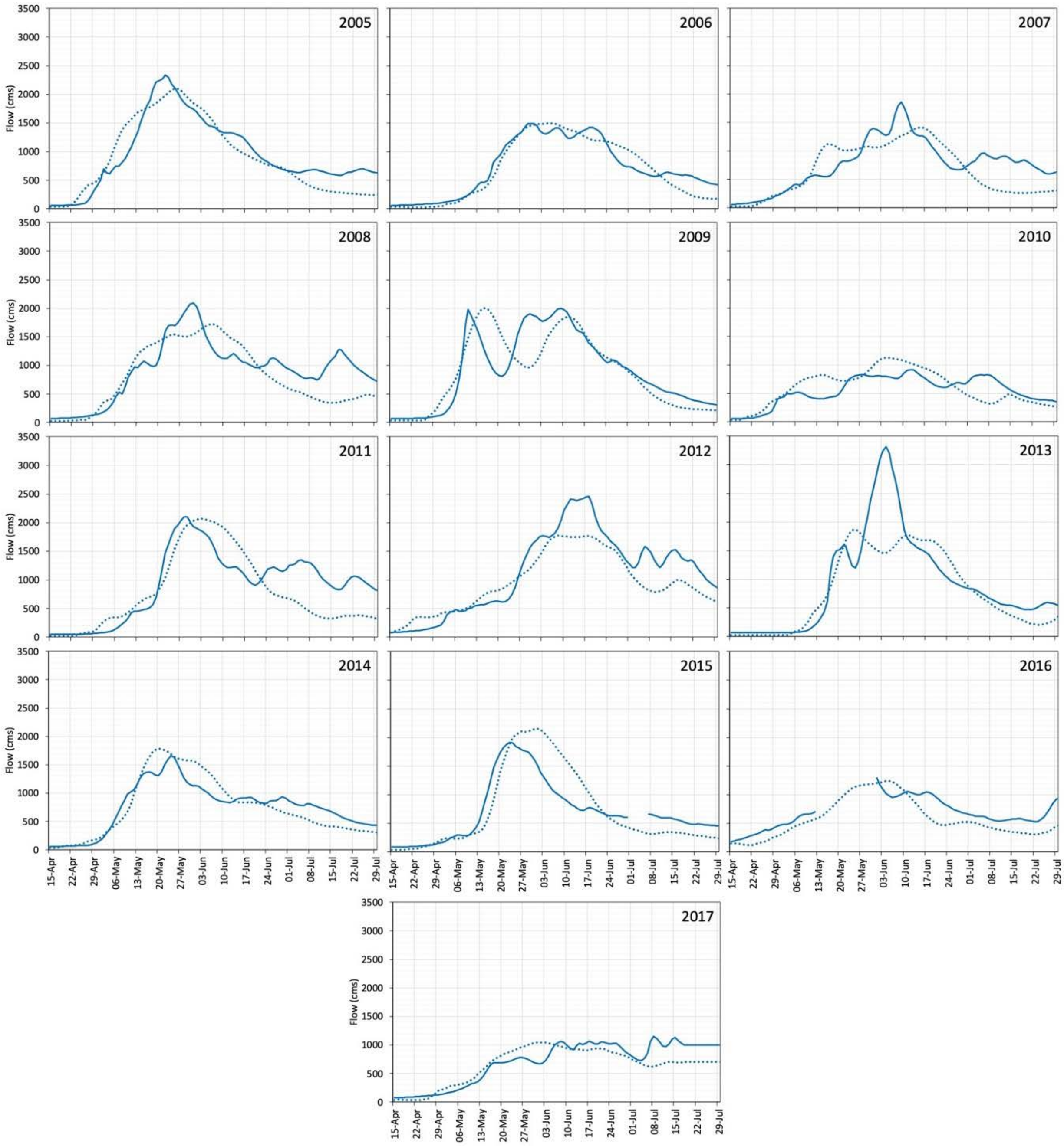


Figure 40: Simulated (dotted line) versus observed (solid line) flows of Pelly River at Pelly Crossing

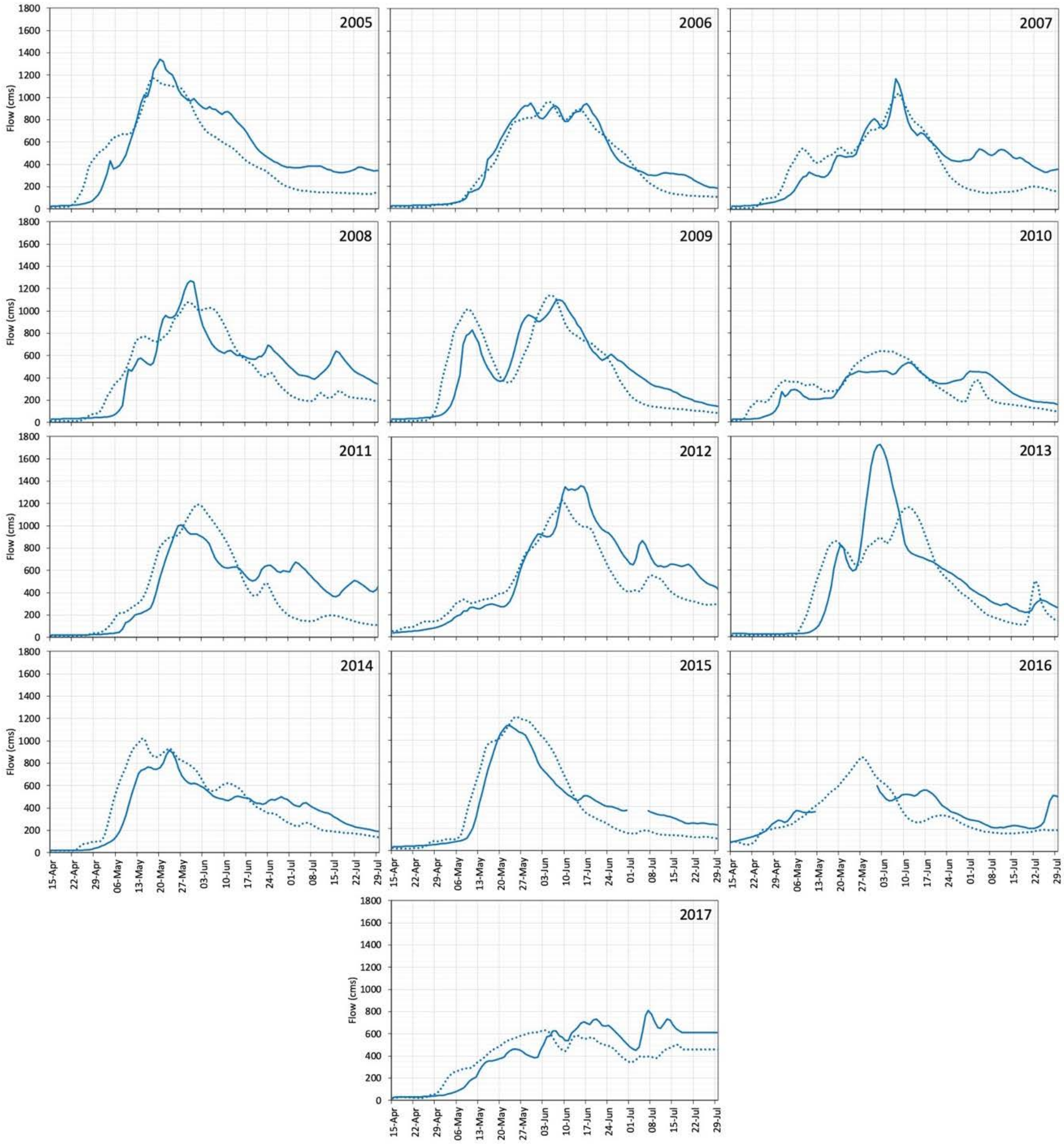


Figure 41: Simulated (dotted line) versus observed (solid line) flows of Pelly River below van Gordra Creek

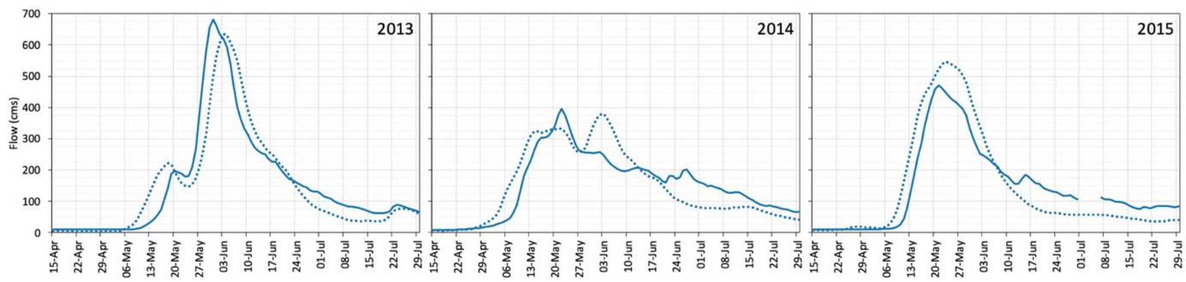


Figure 42: Simulated (dotted line) versus observed (solid line) flows of Pelly River below Fortin Creek

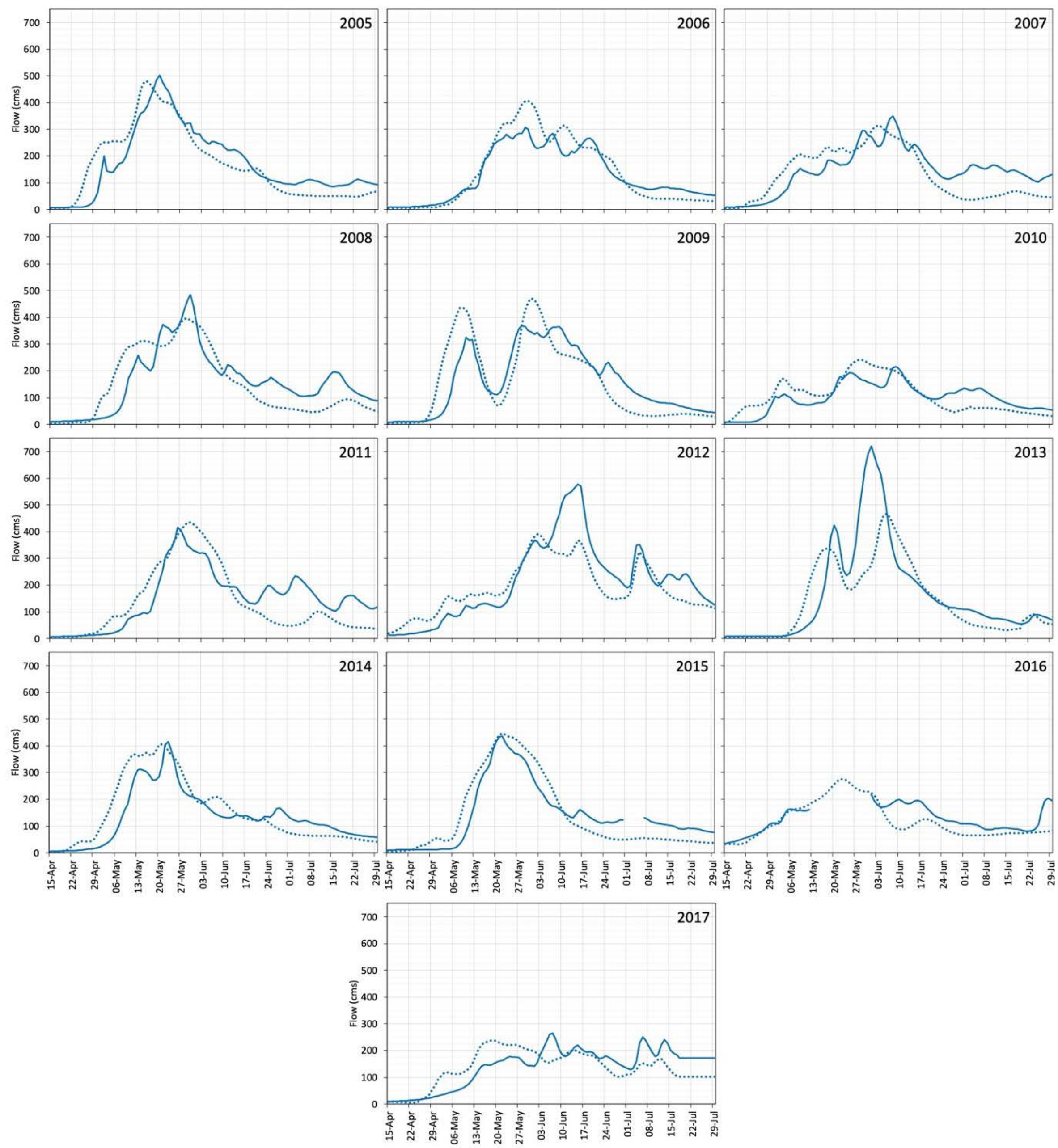


Figure 43: Simulated (dotted line) versus observed (solid line) flows of Ross River at Ross River

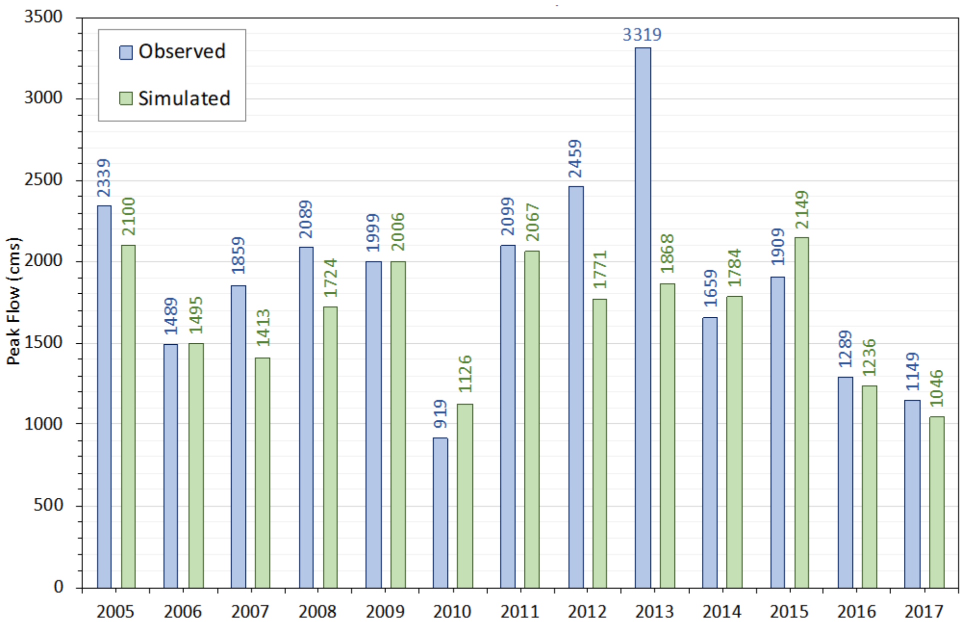


Figure 44: Comparison between observed and simulated peak flows of the Pelly River at Pelly Crossing (09BC001)

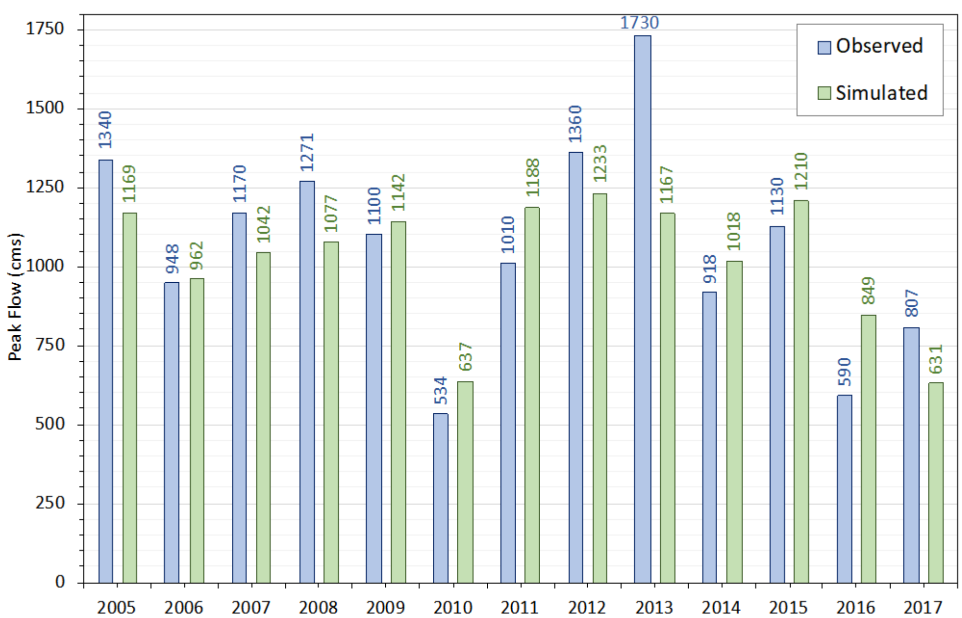


Figure 45: Comparison between observed and simulated peak flows of the Pelly River below van Gorda Creek (09BC004)

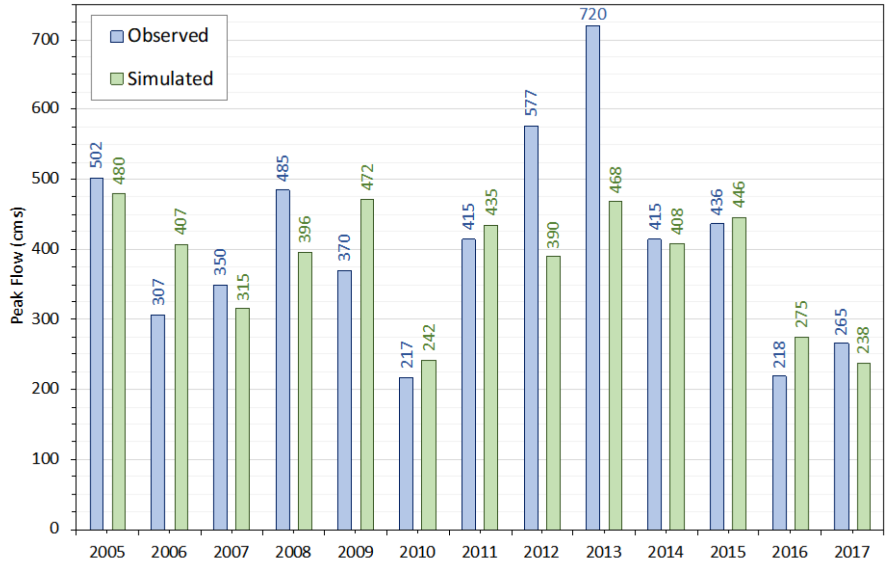


Figure 46: Comparison between observed and simulated peak flows of the Ross River at Ross River (09BA001)

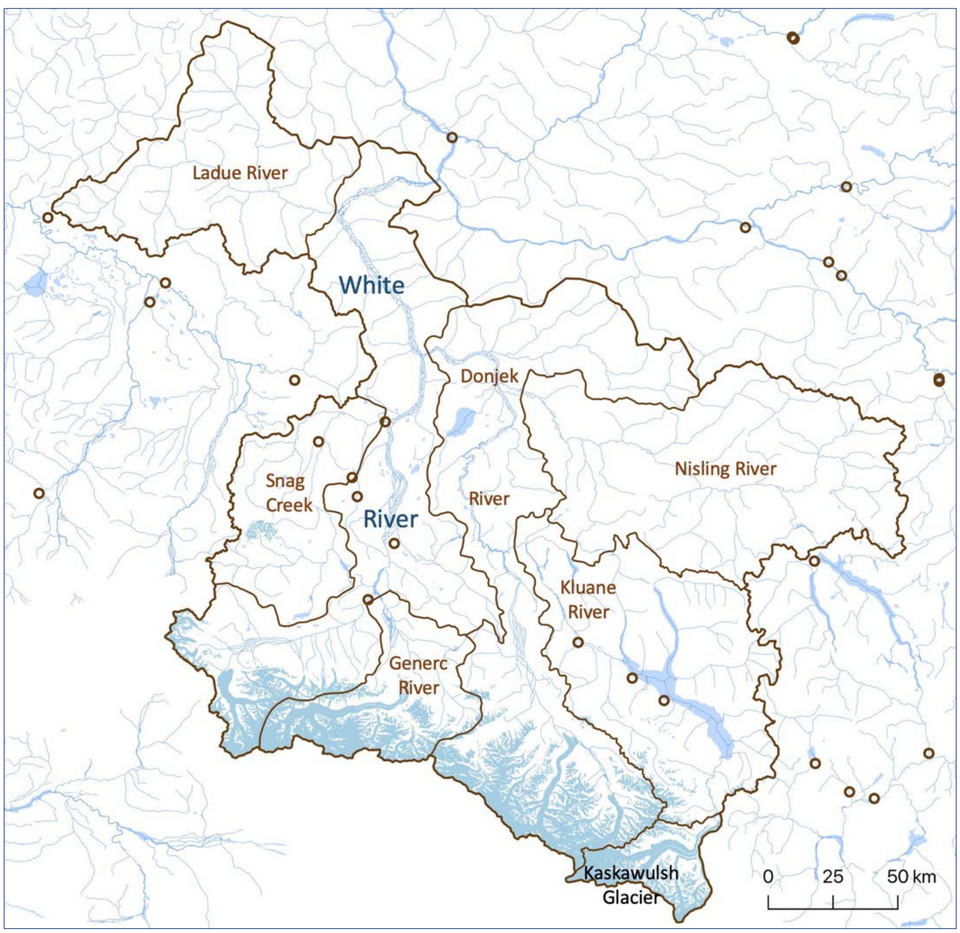


Figure 47: Sub-basins of White River; Kaskawulsh Glacier drainage discontinued in 2016

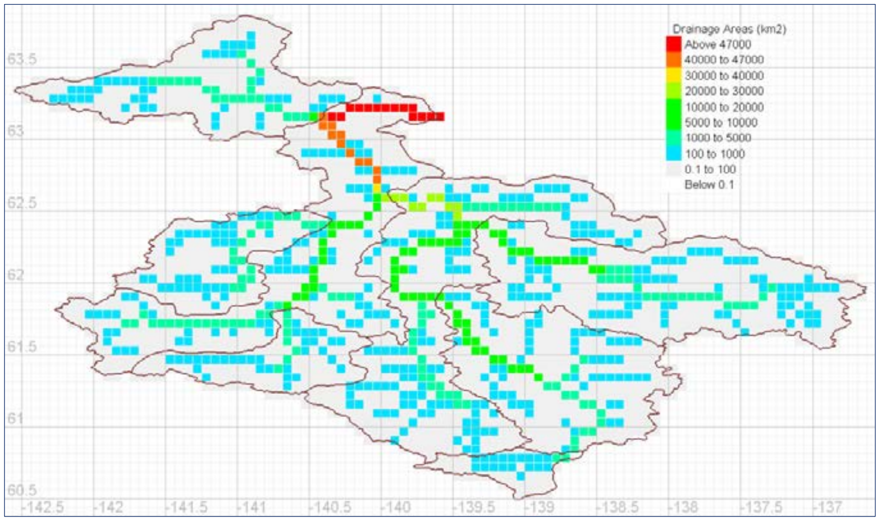


Figure 48: Discretized drainage areas of White River at 0.0625° spatial resolution

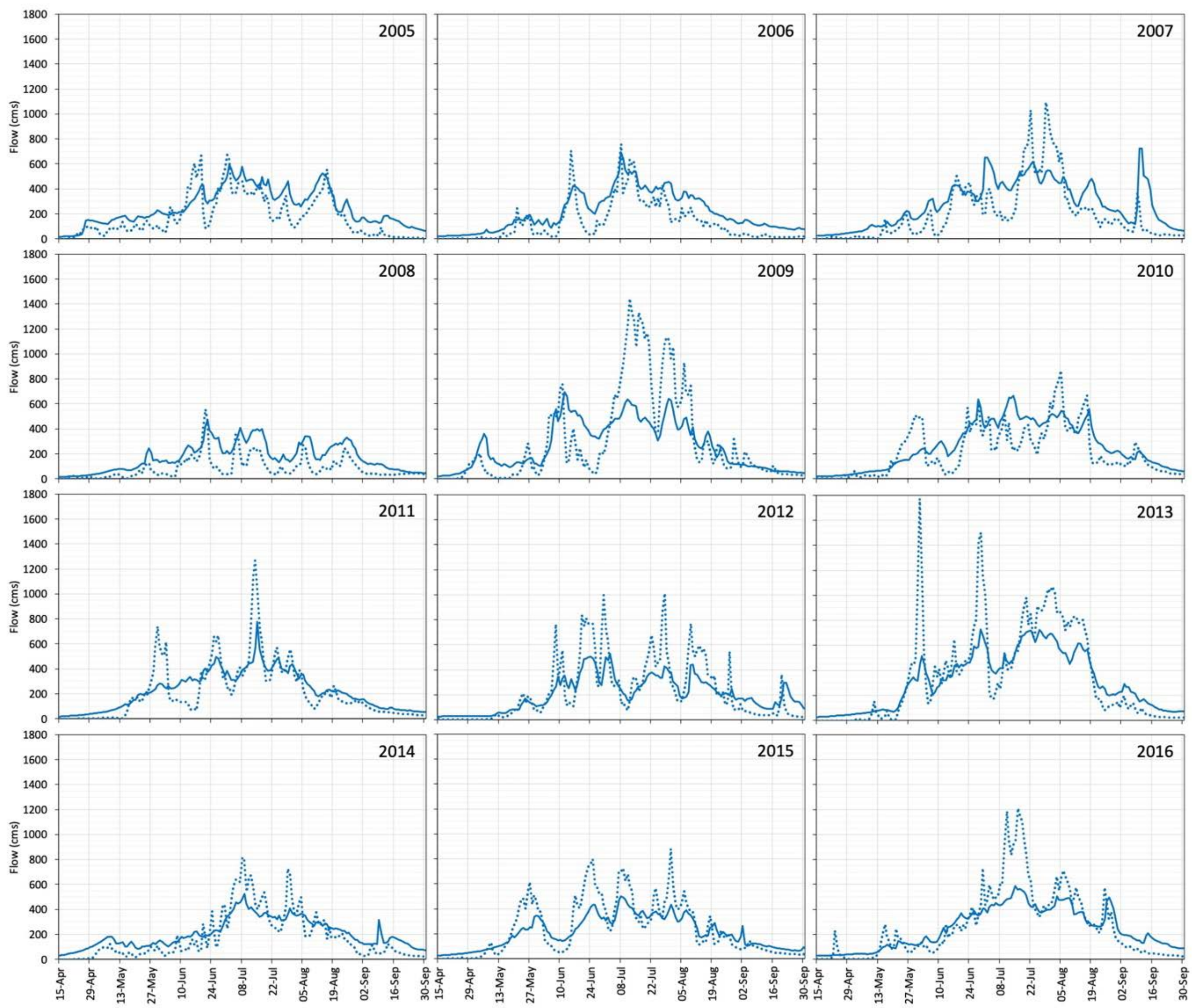


Figure 49: Simulated (dotted line) versus observed (solid line) flows of the White River at km 1881.6 Alaska Highway

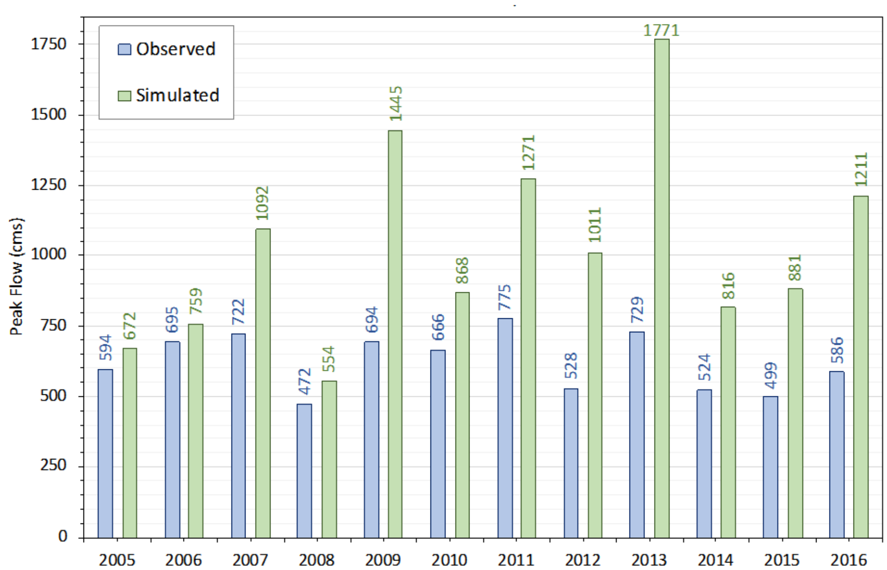


Figure 50: Comparison between observed and simulated peak flows of the White River at km 1881.6 Alaska Highway (09CB001)

6. Forecasting System Operation and Assessment

The Yukon Forecasting System consists of a set of scripts to download and prepare meteorological forcing data (from ECCC Regional and Global Deterministic Prediction Systems - RDPS and GDPS) and run MESH for a set of model setups. The latter were prepared and organized in separate folders and provide streamflow forecasts at designated forecast points (Table 1). The following sections give a brief overview of the automated system.

6.1 Folder Structure

The system has a relatively rigid folder structure (Figure 51) as to where downloaded, intermediate and processed files are stored such that the models run automatically every day at designated times to produce the hydrologic forecasts. The main folders are setup beforehand where the system generates additional folders daily to run the models, save their results, and postprocess them for plotting the forecasted streamflow, simulated water balance components, as well as recent observations when available. This system relies on a few configuration files that provide details about the data files to download, the model setups to run, and the stations to generate the forecasts at. The system is hosted on the Amazon Elastic Compute Cloud (EC2) which is provided by Amazon Web Services (AWS). Table 13 gives details about the main folder structure of the Forecasting System.

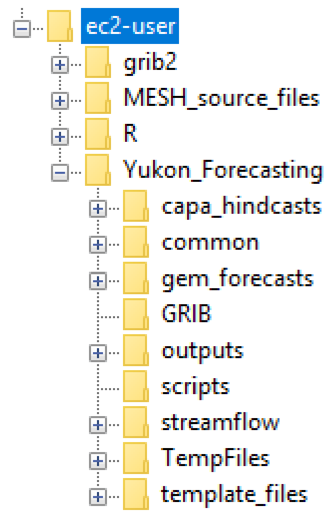


Figure 51 Main Folders of the Forecasting System

Table 13 Folders on the EC2 cloud and their functions

Folder*	Function/Use
grib2	Holds the grib package which is used the extract the meteorological forcing downloaded from ECCC datamart (in GRIB format) for the different sub-basin setups
MESH_source_files	Holds the code and executables that are used to run MESH
R	Holds the R software package that is used mainly for plotting forecasts
Yukon_Forecasting	This is the main folder of the forecasting system
capa_hindcasts	This where the processed CaPA data is stored and MESH runs for all setups are run storing necessary initial conditions to start the forecast runs
common	This folder holds the static model setup files for each sub-basin MESH setup
gem_forecasts	This where the processed forecast forcing data is stored and MESH runs for all setups are run storing necessary outputs to produce the forecast plots
GRIB	Holds files for CaPA, RDPS and GDPS downloaded daily from ECCC datamart
outputs	Holds the final forecast plots as well as some intermediate outputs
scripts	Holds all scripts and configuration files necessary to run the system
streamflow	Holds downloaded streamflow observations for designated stations and an archive of historical observations for those stations
TempFiles	Holds temporary files generated during the processing of forcing data – cleaned at the end of processing
template_files	Holds semi-static model setup templates that gets updated with each run (hindcast, RDPS forecast, GDPS forecast)

* Folder and file names are all case sensitive

6.2 Initial System Setup

Under "common" and "template_files", a folder for each sub-basin setup needs to be created and populated with the static MESH setup files (drainage database, parameters, etc.). A folder for each MESH setup requirements is created under "capa_hindcast", "gem_forecasts" as well, where the MESH runs are performed and outputs are saved. Another folder named after each station should also be created under "streamflow". The system scripts then create daily folders for the runs and populates them during the different processing stages. The "outputs" folder has to have 4 sub-folders named: "Forecast_Plots", "logs", "R_Data_Frames", and "water_balance". Folders can be named differently but this will necessitate updates to all scripts and configuration files that read and store data in them. Furthermore, Initial conditions need to be provided for the very first run of the season. Afterwards, they are automatically saved after each RDPS-CaPA hindcast simulation to be used for the next day forecast.

6.3 Forecast Workflow

One forecasting run consists of a CaPA hindcast and two GEM forecasts using the MESH system (Figure 52). The 24-hour CaPA hindcast, from 16:00 PST two days before the day of forecast, updates the sub-basin hydrologic variables and states using CaPA precipitation data (modelled with assimilated observations as available) and RDPS forecast data for other variables. A 48-hour RDPS forecast follows and starts from 16:00 PST one day before the day of forecast and extends until 16:00 PST the day after the day of forecast. A 10-day GDPS forecast starts at 16:00 PST one day before the day of the forecast for 234 hours (10 days less than 6 hours) later at 07:00 PST, 9 days after the forecast day. Given that the GDPS run starts at 16:00 on the day before the forecast issue, and the forecast is issued on the day of the forecast (at 7:00am CST), the actual lead time is about 9 days.

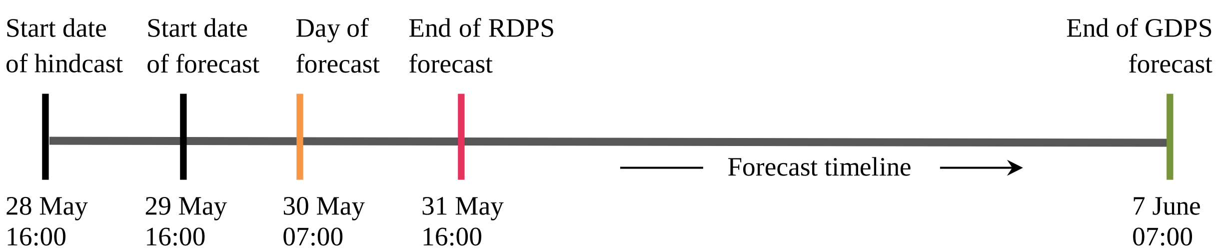


Figure 52 Forecast timeline. Each forecast includes a 24-hour hindcast followed by a 2-day and a 9-day forecast. An example with real dates is also shown.

The workflow starts by downloading GDPS and RDPS forecast data and CaPA data from ECCC datamart database. Meteorological Forcing data for each sub-basin is then prepared from these datasets and stored in daily created folders under "gem_forecasts" and "capa_hindcast" for each MESH model setup. Then the MESH model is run as mentioned above (CaPA-RDPS hindcast then RDPS and GDPS forecasts) to produce discharge rates for the locations specified in the input file MESH_input_streamflow.txt of each MESH setup (to be found under "common"). These locations correspond to hydrometric stations for which observed data is also downloaded. Finally, a set of R scripts post process and generate plots (an example is shown in Figure 53) displaying gauged and modelled discharge at several hydrometric stations, as well as precipitation, evapotranspiration, snowpack and soil moisture from the average water balance of each sub-basin. The content and appearance of the plots are designed to produce more comprehensible, informative and visually clear forecast results. The daily forecast is sent to a predefined list of recipients via email every morning.

6.4 Configuration Files

Two main configuration files are hosted under the "scripts" folder. The first "watersheds.txt" contains details of the MESH model setups (name and grid specifications for data extraction) as well as the list of stations to download observations for. This file provides a one-stop shop that is read by all pre-processing scripts. The second file is "stations_info.txt" which is used by the plotting script to pull the outputs from the respective forecasting folders to produce the plots for designated stations. The current system has a total of 10 model setups (the Main Yukon described in Section 4 and the 5 refined setups described in Section 5 in addition to 4 sub-basin setups produced at an earlier stage of the project). Some model setups produce forecasts for more than one station, and in the same time, some stations are included in more than one setup. With the aid of the stations' configuration files, streamflow plots are produced to include all produced forecasts for a designated station. Through time in the future, and year after year, this will help in assessing the forecasting skill of hydrologic setups with their parameterisations, and ensure flexibility in managing the core of the forecast system in terms of updates and retirements of setups.

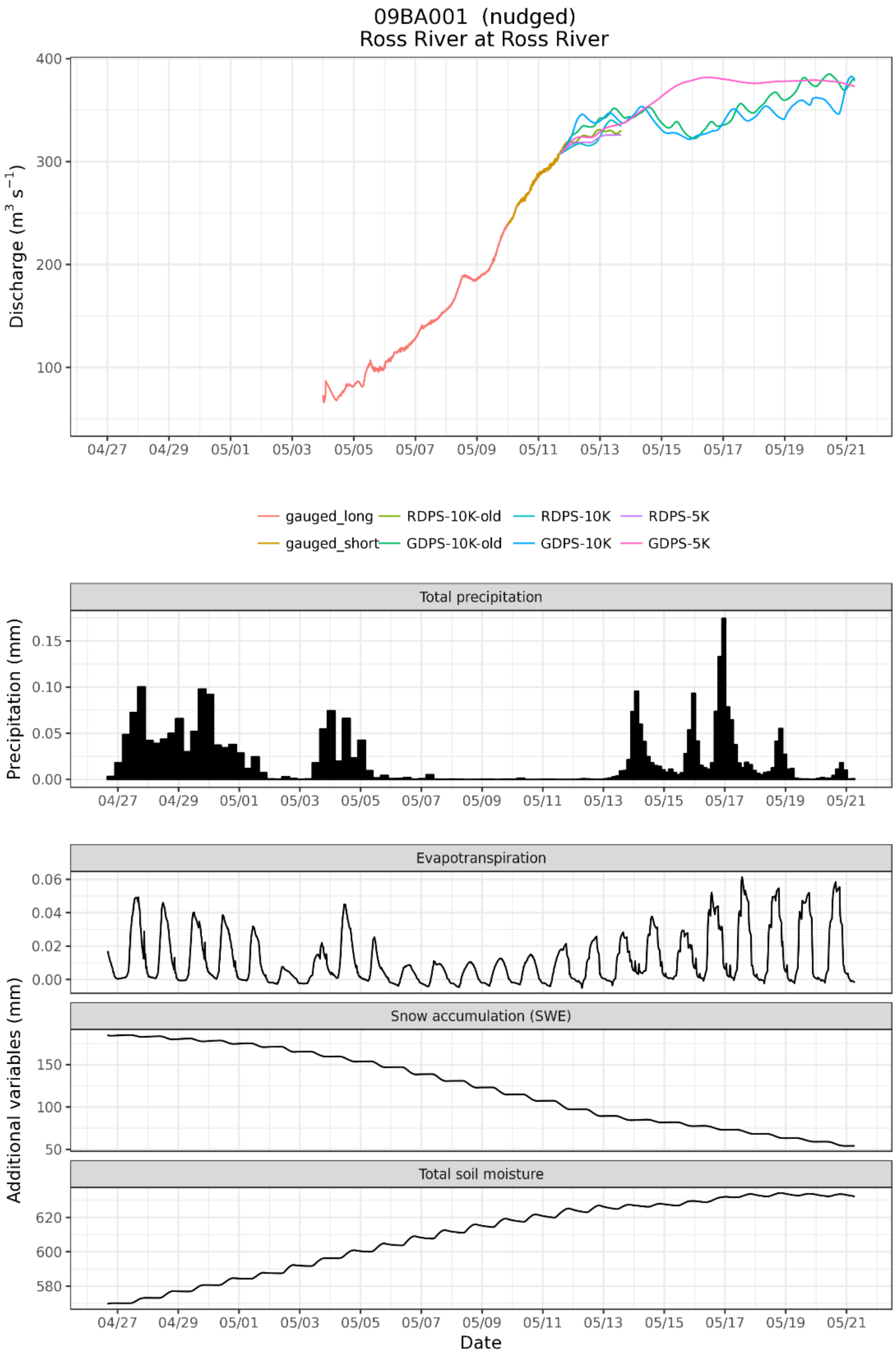


Figure 53 Example Summary Forecast Plots for an Example Station (09BA001). The top panel shows the streamflow forecasts and available observations. The water balance plots show the evolution of two state variables, total soil moisture and snowpack, and two meteorological variables, evapotranspiration and precipitation, for the two weeks preceding the forecast. MESH produces total basin average values in mm for these four variables for 30-minute time intervals

7. Conclusions and Future Development Needs

The Yukon River Basin streamflow forecasting system was developed to provide operational forecasts of streamflow and water balance for the Yukon River Basin upstream of Eagle, AK and the Porcupine River Basin near the international boundary. It provides supplemental high resolution simulations and forecasts for the Klondike, Stewart, Pelly and White Rivers at their mouths. The modelling system uses the MESH model used to simulate the hydrology of each basin. MESH is a state-of-the-art semi-distributed cold regions hydrological land surface model that models both the vertical exchanges of heat and moisture between the land surface and the atmosphere as well has the horizontal transfer of water to streams that is routed hydrologically to the outlet of the basin. It includes snow, frozen soil and glacier processes as well as the full suite of warm season hydrology. MESH is driven by the Environment and Climate Change Canada GEM weather model and hindcasts are driven by GEM-CaPA which is a data assimilation product that uses local precipitation observations where they exist.

Having MESH run at both 10 km and 5 km resolution provides an assessment of model resolution needed for forecasting and also of model uncertainty in the forecasts. The MESH model was driven by GEM-CaPA for hindcasts and with the GEM ECCC Regional and Global Deterministic Prediction Systems - RDPS and GDPS forecasts for forecasts of 2 and 9 days. The GEM-MESH model showed good to very good predictions in most river basins after calibration and parameter selection, with challenges for the Porcupine and White rivers due to permafrost and wetlands (Porcupine) and to extensive icefields (White) and overall to sparse to non-existent observed precipitation data to assimilate into the CaPA system. It is noted that in some cases there was no correlation between accumulated winter precipitation in the CaPA product and Yukon Environment snow survey observations. The forecast system is capable of providing reliable streamflow predictions and is run with automated scripts on Amazon Web Services.

Future development of the forecasting system should focus on the very challenging permafrost hydrology of the Porcupine River Basin, the active layer dynamics and its impact on the storage and variable contributing area for runoff generation that is likely present in Old Crow Flats. Further development and testing of the glacier component of MESH is needed to improve performance on the White River which drains the largest icefields in North America. The model does not include a river ice component, but one could be added in the future.

The users should take care to understand the model limitations and uncertainty in its forecast advisory products and these advisory products should only be used in developing forests with good hydrological understanding of the rivers and basins involved.

Acknowledgements

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