Advancing, Calibrating, Demonstrating Snow Assimilation and Estimating Ungauged Basin Flow: The Vector-Based MESH Model of the Yukon River Basin

Supplement #2 to Centre for Hydrology Report No. 16,
Yukon River Basin Streamflow Forecasting System

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Executive summary

The Yukon River Basin the second largest river 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, Alaska - just downstream of the international boundary (288,000 km^2). The southern part of the Yukon River basin is characterized by extensive icefields and snowfields 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 by wind, 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 supplement shows further development of a vector-based MESH setup for the Canadian portion of the Yukon River Basin down to Eagle, Alaska. For operational forecasting, MESH is driven by the Environment and Climate Change Canada Global Multiscale Model (GEM) weather model forecasts with precipitation replaced with the Canadian Precipitation Analysis (CaPA) which assimilates local precipitation observations where they exist, collectively referred to as GEM-CaPA. Additionally, the newly developed Regional Deterministic Reforecast System v2.1 (RDRS v2.1) forcing has been extended to span the period 1980-2018 enabling long-term assessments of hydrology. The revised vector-based model was calibrated for operational use based on the GEM-CaPA forcing dataset, and for performing historical simulations based on the RDRS v2.1 forcing dataset, using the period 2004-2011 in both cases. Performance was compared to the previously generated grid-based MESH model whose development was documented in Centre for Hydrology Report #16. A long-term historical simulation was then performed using RDRS v2.1 from which streamflow exceedance return periods for 15 important stations were calculated and presented in this supplement. Calibration has generally improved the performance of the vector-based setup compared to the previous simulations presented in supplement #1 of report #16. Parameter sets are slightly different when the model is calibrated to RDRS v2.1 compared to GEM-CaPA due to differences between the two datasets.

A pilot study of the potential benefits of snow data assimilation into the existing MESH forecast system was conducted using historical data and the gridded MESH product that is used operationally by Yukon Environment. This test showed benefits to assimilating surface snowpack observations into MESH to correct winter precipitation. Outputs with assimilation showed improved snowpack simulations and improved streamflow forecasts.

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1. Introduction

The Yukon River Basin is the 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. It is second largest river basin in the Arctic region of North America. The river originates from the Llewellyn Glacier, BC and flows northwest along a 3,185 km course to discharge into the Bering Sea. The Canadian portion is mostly within 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. MESH was previously set up on the YRB on a fixed grid at 5 and 10 km resolution, depending on the sub-basin. A vector-based setup for the Canadian portion of the Yukon River Basin (with Eagle as the outlet) was also developed and tested using parameters transferred directly from the grid-based setup which resulted in some deterioration of performance compared to the grid-based setup. In the vector-based approach, the actual geometry of river reaches and basins are used for spatial discretization rather than a regular latitude-longitude grids that were used for the grid-based setups documented in the main report. The objective of this work is to further enhance the vector-based MESH model via calibration and use it to conduct a long-term historical simulation (1980-2018) using the newly developed Regional Deterministic Reforecast System v2.1 (RDRS v2.1) forcing dataset. This enables constructing flow duration curves for important locations in the basin. An additional objective is to test the benefits that might be derived from a simple workflow to assimilate ground-based snow observational data into the simulations to improve the model predictions of the snowmelt-derived peak river discharges at important locations in the YRB.

2. Spatial Datasets and Model Development

This MESH application has used the MERIT Hydro global hydrography datasets, developed using the MERIT Hydro DEM and multiple inland water maps to characterize sub-basins and define the model spatial structure and routing (Yamazaki et al., 2019). The drainage database information file for the Main Yukon River Basin, which includes the geophysical parameters of the river network such as river order, channel length, slope and basin areas, was created by processing the MERIT Hydro rivers and basins using in-house scripts. This yielded 6058 modelling subbasins for the entire basin (~289,100 km^2) (Figure 1), to the outlet at the Yukon River at Eagle (09ED001) as shown in Figure 1. The grid-based model has 3448 grid-cells which means that the vector-based setup is generally higher in resolution, especially in the mountain headwaters. However, this varies and about 10% of the headwater basins are larger than 100 km^2. The 6058 sub-basins included very small sub-basins and very short rivers in some headwaters and some intermediate (non-headwater) basins. For this application of MESH, blowing snow redistribution and sublimation are considered important processes in alpine regions, such as the high mountain icefields of the White River. The blowing snow sub-model is implemented to redistribute snow to tiles (GRUs mapped to sub-basins) within each model sub-basin (or grid in the grid-based setup). At length scales of less than ~1 km, redistribution between sub-basins or grid cells as well as redistribution within sub-basins or grid cells would need to be calculated and this capability has not been implemented in MESH. Therefore, the very small sub-basins (area < 1 km^2) were merged into their downstream counterparts to remain within the requirements of the current modelling constraints. This resulted in a setup with 5900 sub-basins, still almost twice that of the original gridded setup for the YRB.

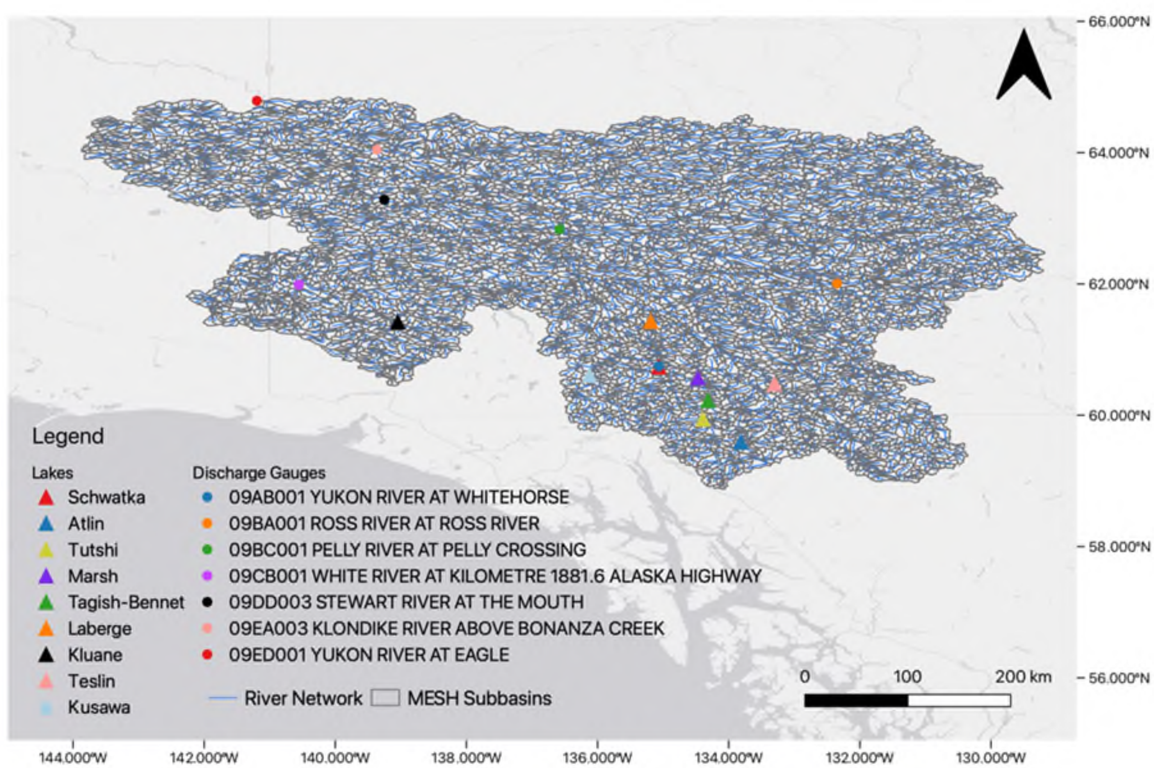


Figure 1: Main Yukon River Basin vector-based MESH model subbasins and rivers, outlets of important lakes and discharge gauges

Model computational speed was slowed down by the existence of very short rivers (< 1 km) in the MERIT Hydro database, forcing MESH to iterate in more loops to solve the routing equations. This was overcome by assuming the length for rivers in headwater catchments to be proportional to the square root of the sub-basin area. This greatly reduced the number of short rivers but still some in non-headwater subbasins had rivers that were too short. Rivers in non-headwater subbasins connect confluences and thus it is no possible to change river lengths. These were further improved by increasing the capacity of the river cross section through refitting the parameters of the river capacity equation using a newly developed dataset for river width (Lin et al., 2019) that is also based on MERIT-hydro DEM. Ideally, river width from this dataset should have been used directly to calculate cross-sectional capacities of reaches. However, the dataset had width values for only 2900 reaches in the YRB out of 6058. Therefore, we fitted the river capacity equation (a relationship between river capacity and cumulative drainage area) to be able to benefit from the dataset for all river reaches. Both of these changes reduced the need for excessive iterations and reduced the run-time of the model. However, the higher number of subbasins (5900) compared to the number of grids in the grid-based setup (3448) meant that we have 61% more computational elements for the vector-based setup and that it runs slower than the grid-based one.

The vector-based model setup was configured to include the same important lakes (Figure 1) used in the grid-based setup, for which the outflow relationship parameters were transferred from the grid-based setup (Elshamy et al., 2020). Unlike the grid-based setup, the vector-based setup does not require any corrections of flow directions which is a huge advantage in terms of model development time and its accuracy. However, the locations of the stations and lake outlets had also to be manually adjusted to fall within the correct subbasin.

Rivers were classified into seven river classes based on the river order which is given directly by the MERIT-hydro Basins dataset as the Strahler order. This is an additional advantage of the vector-based setup. Here Class 1 refers to headwater rivers, whilst Class 7 refers to the largest rivers (Figure 2). The grid-based setup used 5 river classes where Class 1 was the largest and Class 5 was the smallest (see Elshamy et al., 2020).

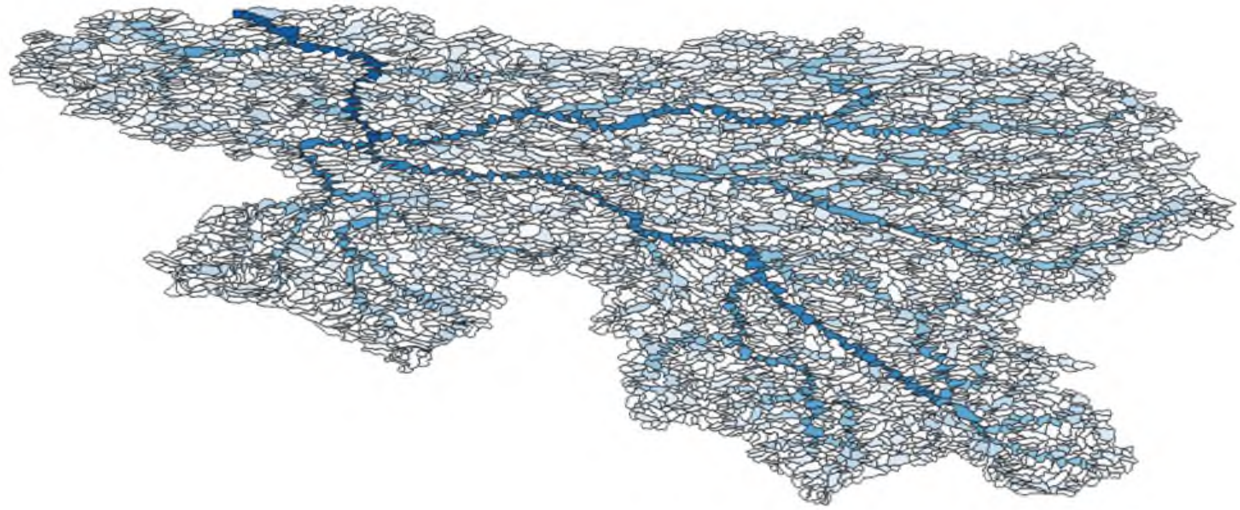


Figure 2 River Classes for the vector-based setup (darker colors indicate larger rivers at higher classes)

The 30 m LANDSAT version of the 2010 NALC dataset (CCRS et al., 2017) was used to create MESH grouped response units (GRUs). Following the methodology used for the grid-based MESH model setup of the Main Yukon River Basin, GRU discretization was performed based on the land cover types and slope and aspect categories, which yielded 12 GRUs (Figure 2 of Supplement #1) which is the same number as for the grid-based setup to facilitate parameter transfer/comparison. Including slope and aspect GRUs and parameterizing for elevation differences within a sub-basin has been shown to improve MESH performance in mountain basins, although it has not been activated yet for this model setup. The model parameters for each of these GRUs and river routing parameters were initially transferred from the grid-based MESH setup (Elshamy et al., 2020). Additionally, the blowing snow module for the vector-based model was turned on and the grid-based model with blowing snow turned on was rerun to make them more comparable. The order of down-wind GRUs and their related blowing snow parameters were taken from other studies, namely the Mackenzie and the Saskatchewan River basin setups and field studies in Wolf Creek, Yukon.

The meteorological variables to run MESH, namely incoming shortwave radiation, incoming longwave radiation, total precipitation rate, air temperature, wind speed, barometric pressure and specific humidity were obtained from two datasets: Global Multiscale Model (GEM) with precipitation replaced by the Canadian Precipitation Analysis (CaPA) (GEM-CaPA; Côté et al., 1998; Mahfouf et al. 2007) and the Regional Deterministic Reforecast System v2.1 (RDRS_v2.1; Gasset et al., 2021). The meteorological inputs are available for 2004-2017 and 1980-2018 from GEM-CaPA (GC) and RDRS v2.1, respectively. The gridded meteorological variables were remapped over the 5900 subbasins of the vector-based setup (Figure 1) using the Earth System Modeling Remapper (EASYMORE; https://github.com/ ShervanGharari/ EASYMORE). Hereon, GEM-CaPA forced MESH is referred to as GC-MESH and RDRS v2.1 forced MESH is referred to as RDRS-MESH.

MESH was then calibrated once using RDRS v2.1 forcing and once using GEM-CaPA forcing. The period 2004-2011 was used for calibration in both cases. The calibrated RDRS-MESH model was then run using RDRS v2.1 for the whole period 1980-2018 to produce flow and level duration curves at important stations in the basin. The calibrated GC-MESH was intended to be used to test a snow assimilation algorithm aiming to improve the snowmelt peak streamflow by adjusting the precipitation over the snow accumulation period. However, due to the slowness of the vector-based setup, we used the grid-based setup to do this test. The procedure is applicable to the vector-based setup. For all simulations using the grid-based and vector-based setups, we used r1860 of the MESH code, which fixes some issues compared to the code used for the previous simulations (Elshamy et al., 2020 and Aygun et al., 2022).

3. Calibration Results and Performance

For calibration runs, the GC-MESH and RDRS-MESH model simulations were initialized on Sep 1, 2004 and run to Dec 31, 2015. The period between Sep 1, 2004 and Dec 31, 2005 was considered a spin-up period and was not included in the calculations of error metrics. After calibration, the model was run for an evaluation period spanning the period 2006-2015 with a proper initialization procedure. In this the model was initialized on Sep 1, 2004 to be able to assume snow-free conditions and run till Dec 31, 2004, then the first full year of record (2005) was run for 5 cycles, repeating the forcing from Jan 1 - Dec 31, 2005 before the main run is started from Jan 1, 2006. This initialization procedure improves flows in glaciated headwater basins and those with lakes. Although RDRS v2.1 forcing is available from 1980, this period was selected as a common period to compare model performance under the different forcing datasets. Because there were high PBIAS values for some sub-basins, the full set of parameters was calibrated as was initially done for the grid-based setup (Tables 6 and 7 of the Elshamy et al., 2020), but extended to the routing parameters of 7 river classes instead of the 5 that were in the grid-based setup. Unlike calibration of the grid-based MESH, water balance and routing parameter were calibrated in one step to maximize the sum of KGE for 7 gauged stations (listed on Figure 1). The metrics of MESH-Vector simulations using the parameters transferred directly from MESH-grid, and those calibrated in this manner are compared in Table 1 and 2 to the grid-based setup forced by GC and RDRS data respectively.

Table 1: Performance of the grid-based and vector-based models at the discharge gauges of interest (Figure 1) over the evaluation period (2006-2015) using GEM-CaPA forcing. Numbers in red/black/green indicate reduced/unchanged/improved performance, respectively. GC-MESH-Vector with transferred parameters is compared to GC-MESH-Grid while GC-MESH-Vector with calibrated parameters is compared to the one with transferred parameters.

Gauge	GC-MESH-Grid		GC-MESH-Vector Transferred Parameters		GC-MESH-Vector Calibrated Parameters	
	KGE	PBIAS	KGE	PBIAS	KGE	PBIAS
09AB001	0.91	3%	0.84	8%	0.90	-1%
09BA001	0.83	8%	0.77	10%	0.78	-4%
09BC001	0.89	1%	0.87	-1%	0.79	-15%
09CB001	0.42	8%	0.29	17%	0.34	16%
09DD003	0.76	3%	0.72	3%	0.78	-8%
09EA003	0.77	-13%	0.74	-13%	0.67	-20%
09ED001	0.92	-2%	0.90	-1%	0.85	-12%

The metrics for GC-MESH-Grid and RDRS-MESH-Grid differ from those reported in Supplement #1 (Table 2 in Aygun et al., 2022) due to enabling the blowing snow module and using a slightly different initialization procedure as described above. For both forcing datasets, transferring the parameters directly from the grid-based MESH deteriorated the metrics slightly, especially for the basins 09AB001 and 09CB001 where the headwaters are glaciated when using GC and for 09DD003 when using RDRS. Calibration improved the metrics for most stations but not to the same level of the grid-based model. Improvement of KGE generally indicates improvements in PBIAS but not always. Calibration of the MESH-Vector under RDRS improved the model compared to the transferred parameters for almost all stations and both KGE and PBIAS. The improvement is more marked in this case because the transferred parameters are coming from the grid-based model that was originally calibrated to GC. In this case, the calibration succeeded in reaching or exceeding the performance of MESH-Grid under RDRS but still fell short from the values of GC-MESH-Grid for most metrics/stations. The performance of the vector-based setup is slightly inferior to the grid-based setup for GC but closely matches that of the grid-based one for RDRS. Note that the MESH-Grid was not calibrated to RDRS. Comparing RDRS vs GC, the White (09CB001) river basin shows improvement but some other large tributaries like the Stewart (09DD003) and the Klondike (09EA003) deteriorated.

Table 2: Performance of the grid-based and vector-based models at the discharge gauges of interest (Figure 1) over the evaluation period (2006-2015) using RDRSv2.1 forcing. Numbers in red/black/green indicate reduced/unchanged/improved performance, respectively. GC-MESH-Vector with transferred parameters is compared to GC-MESH-Grid while GC-MESH-Vector with calibrated parameters is compared to the one with transferred parameters.

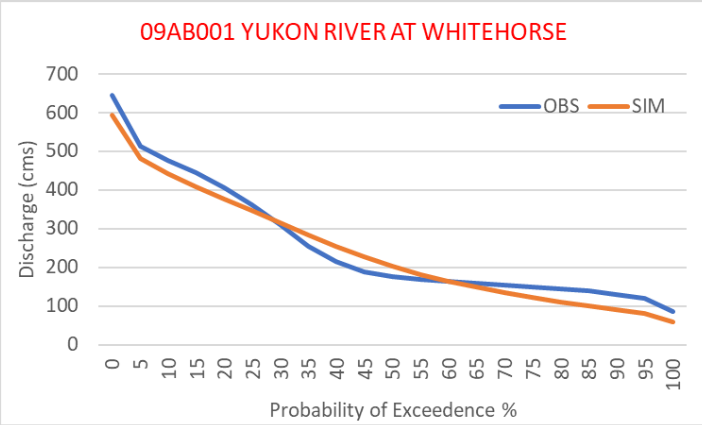
Gauge	RDRS-MESH-Grid Transferred from GC-MESH-Grid		RDRS-MESH-Vector Transferred Parameters		RDRS-MESH-Vector Calibrated Parameters	
	KGE	PBIAS	KGE	PBIAS	KGE	PBIAS
09AB001	0.87	-5%	0.92	-1%	0.90	3%
09BA001	0.81	10%	0.76	12%	0.80	0%
09BC001	0.81	10%	0.80	9%	0.83	-11%
09CB001	0.66	-3%	0.57	3%	0.33	19%
09DD003	0.61	21%	0.57	21%	0.80	-5%
09EA003	0.64	15%	0.55	18%	0.70	-17%
09ED001	0.89	2%	0.86	5%	0.87	-6%

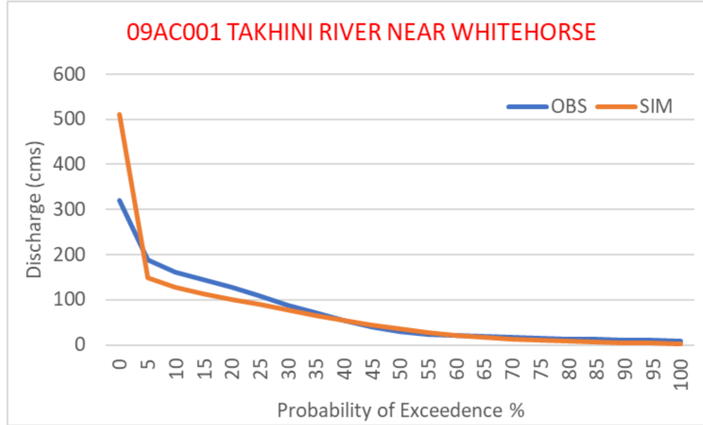
4. Development of Flow and Level Duration Curves

The RDRS-MESH calibrated model was run for the whole period of the RDRS v2.1 record (1980-2018). The model was initialized on Sep 1, 1980 to be able to assume snow-free conditions and run till Dec 31, 1980. then the first year of record was run for 5 cycles (repeating the forcing from Jan 1 - Dec 31, 1980) to properly initialize glaciers and lakes. For this model simulation, the blowing snow module was turned on and was parameterized based on previous studies as mentioned above. The 39-year run was then processed to produce the FDC curves (Figure 3) at the locations listed in Table 3, some of which were ungauged for partial or complete periods. The simulated FDCs closely match those based on observation for most stations, especially those having reasonably complete observational records. When the observational record is short, e.g., 09EB001, the reliability of the observation based FDC is thought to be low. For some stations, e.g., 09AC001, the peaks were over-estimated by MESH-RDRS and therefore, the observed and simulated FDCs have mismatches at high flows (low exceedance probabilities). FDCs can optionally be produced at any desired location based on the simulation results.

Table 3 List of Important Stations with % completeness of record during the period 1980-2018

Station	Station Name	% Complete	Remarks
09AB001	YUKON RIVER AT WHITEHORSE	96.8%	
09AC001	TAKHINI RIVER NEAR WHITEHORSE	97.0%	
09AH001	YUKON RIVER AT CARMACKS	41.0%	Flow record ends 1995
09AH004	NORDENSKIOLD RIVER BELOW ROWLINSON CREEK	93.6%	
09BC001	PELLY RIVER AT PELLY CROSSING	100.0%	
09BC002	PELLY RIVER AT ROSS RIVER	0.0%	Only Levels are available
09BC004	PELLY RIVER BELOW VANGORDA CREEK	100.0%	
09CB001	WHITE RIVER AT KILOMETRE 1881.6 ALASKA HIGHWAY	96.4%	
09CD001	YUKON RIVER ABOVE WHITE RIVER	100.0%	
09DC006	STEWART RIVER NEAR MAYO	0.0%	Only Levels are available
09DD003	STEWART RIVER AT THE MOUTH	99.6%	
09DD002	STEWART RIVER AT STEWART CROSSING	0.0%	Discontinued since 1973
09EA003	KLONDIKE RIVER ABOVE BONANZA CREEK	100.0%	
09EA006	KLONDIKE RIVER AT ROCK CREEK	0.0%	Only Levels are available
09EB001	YUKON RIVER AT DAWSON	2.6%	Only 1980 has flow record


09AB001 YUKON RIVER AT WHITEHORSE
OBS
SIM
Discharge (cms)
700
600
500
400
300
200
100
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Probability of Exceedence %


09AC001 TAKHINI RIVER NEAR WHITEHORSE
OBS
SIM
Discharge (cms)
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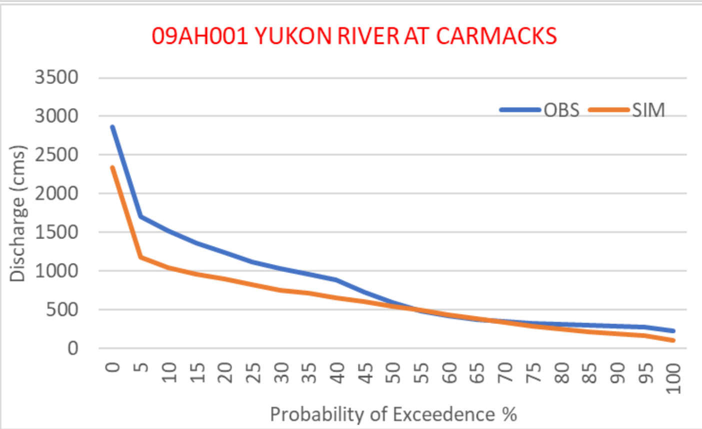
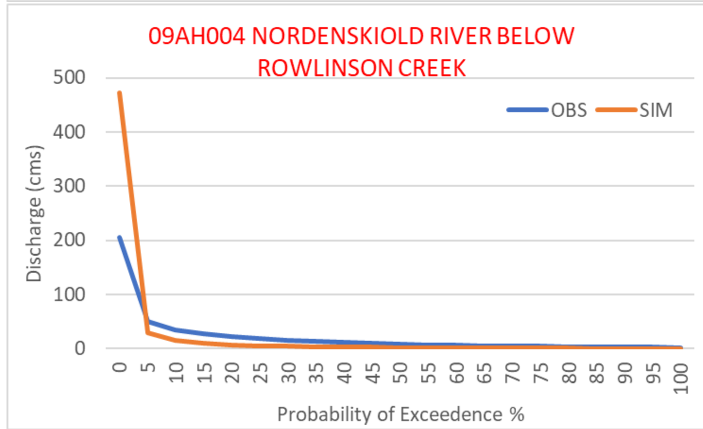
500
400
300
200
100
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Probability of Exceedence %


09AH001 YUKON RIVER AT CARMACKS
OBS
SIM
Discharge (cms)
3500
3000
2500
2000
1500
1000
500
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Probability of Exceedence %


09AH004 NORDENSKIOLD RIVER BELOW ROWLINSON CREEK
OBS
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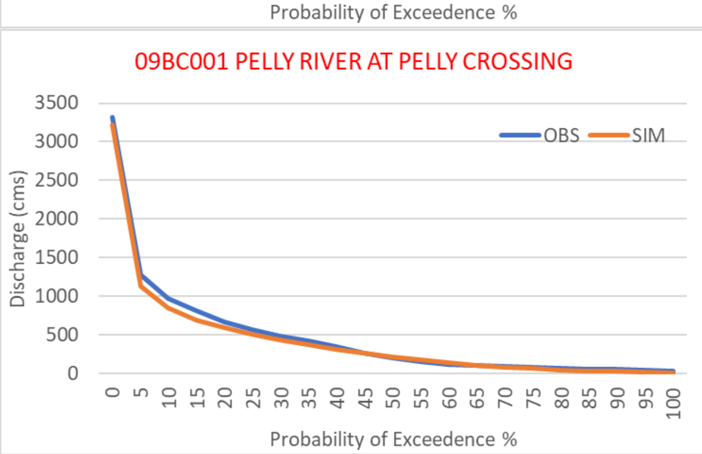
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Probability of Exceedence %


09BC001 PELLY RIVER AT PELLY CROSSING
OBS
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Discharge (cms)
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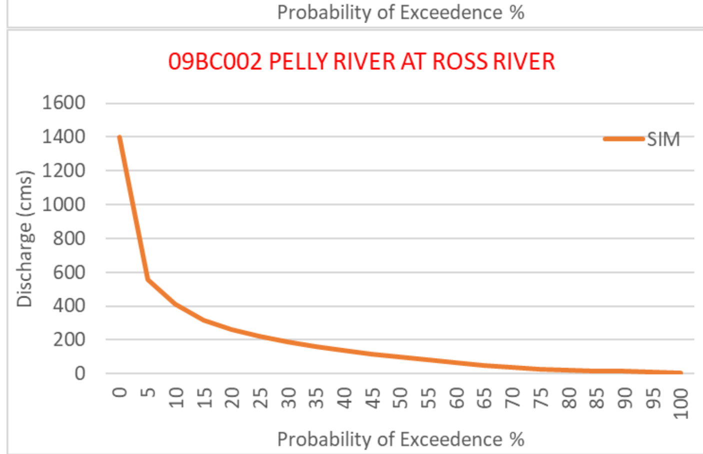
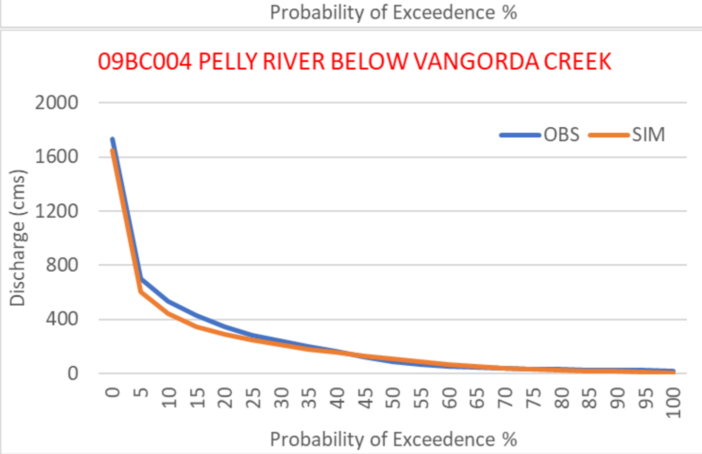
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Probability of Exceedence %


09BC002 PELLY RIVER AT ROSS RIVER
SIM
Discharge (cms)
1600
1400
1200
1000
800
600
400
200
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Probability of Exceedence %


09BC004 PELLY RIVER BELOW VANGORDA CREEK
OBS
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Discharge (cms)
2000
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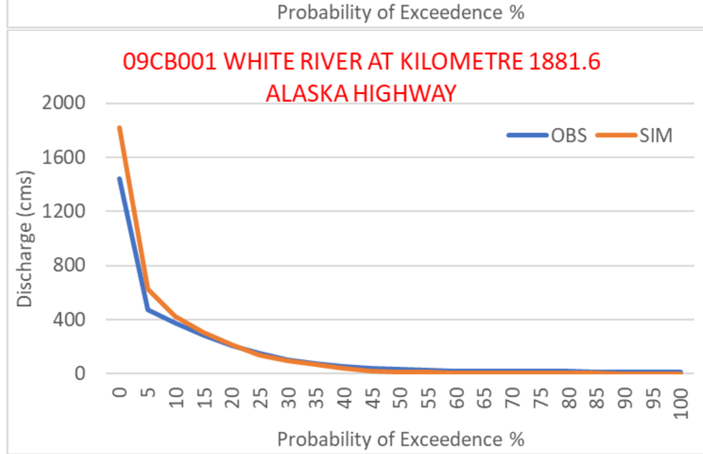
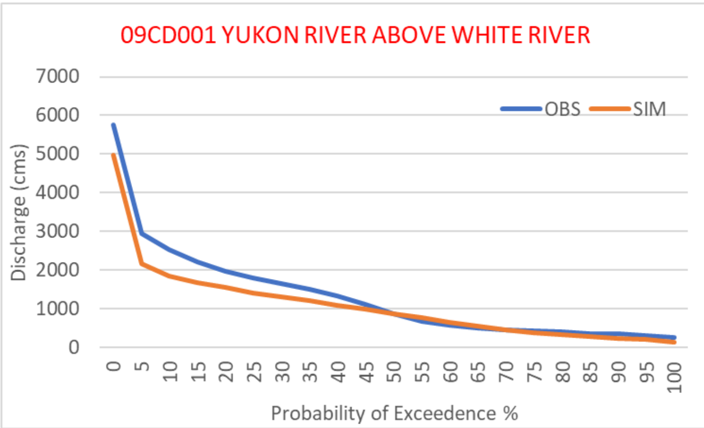
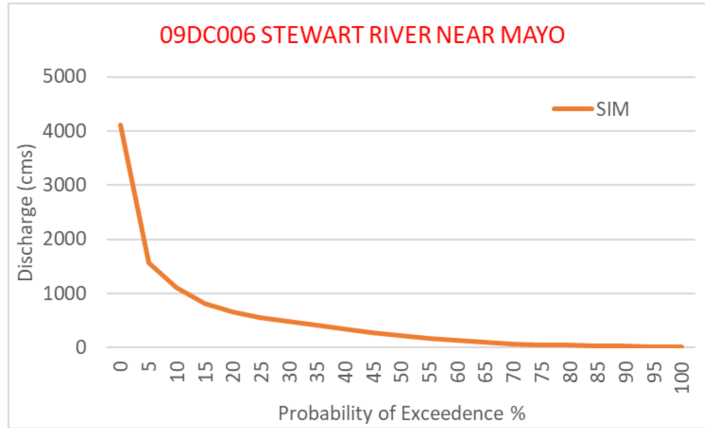
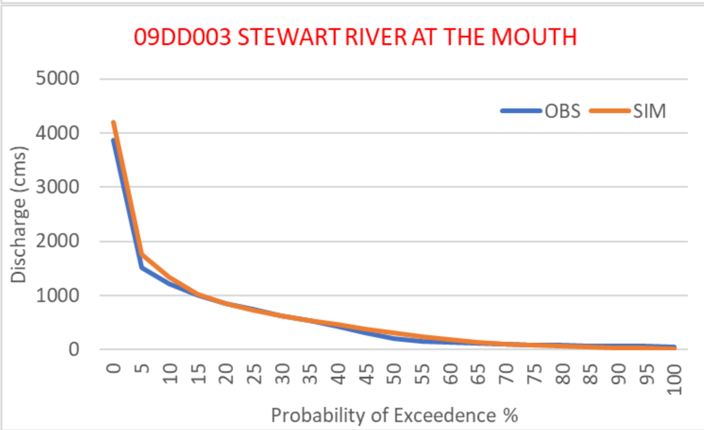
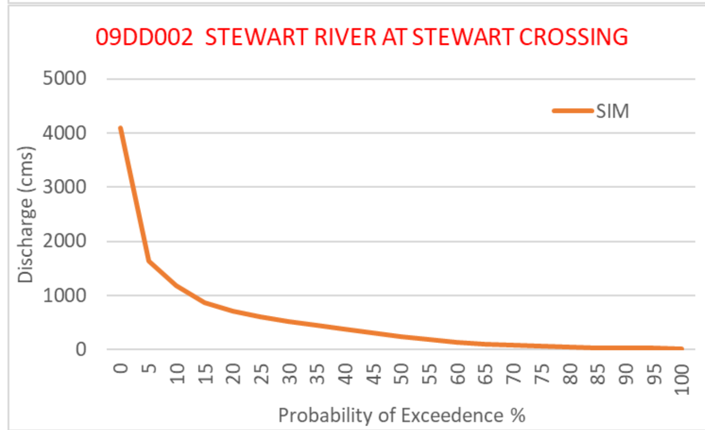
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Probability of Exceedence %

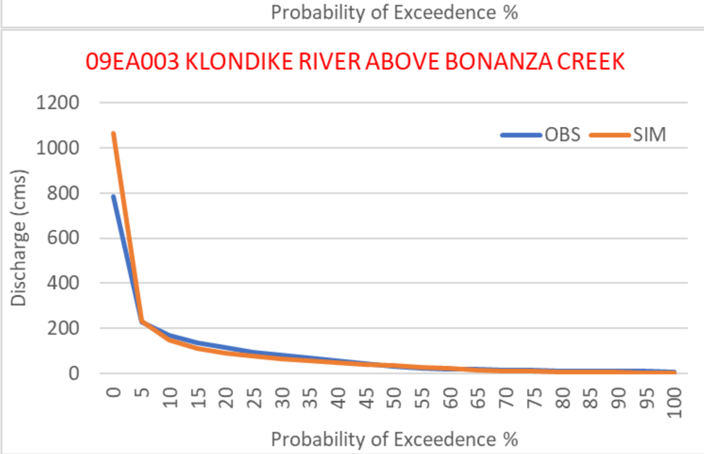

09CB001 WHITE RIVER AT KILOMETRE 1881.6 ALASKA HIGHWAY
OBS
SIM
Discharge (cms)
2000
1600
1200
800
400
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Probability of Exceedence %

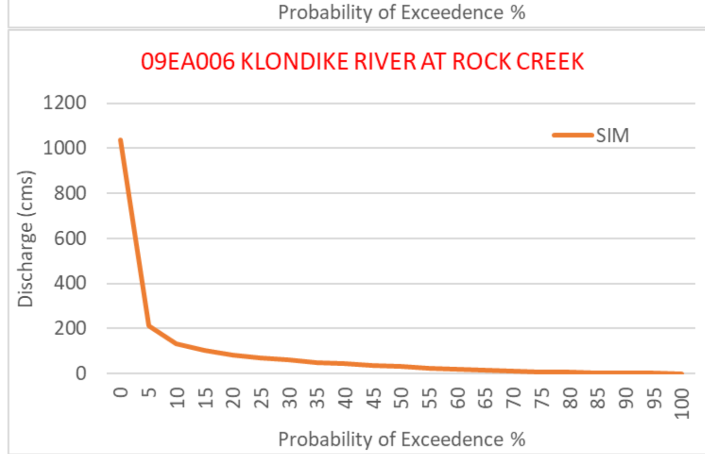












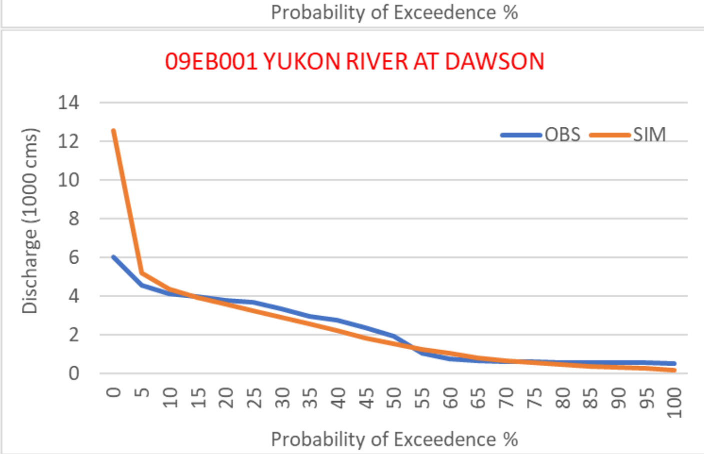


Figure 3 Flow Duration Curves for Important Stations in the Yukon River Basin. FDCs for observations are based on available records which vary per station – see Table 3.

The MERIT-hydro basins dataset does not consider lakes as individual sub-basins and therefore lakes had to be designated in a similar way to the grid-based setup. Thus, they are not properly resolved. For example, Figure 4 shows the sub-basins assigned to Lake Teslin in comparison to the actual lake as taken from the Canadian Water Atlas (open.canada.ca/data/en/dataset/e9931fc7-034c-52ad-91c5-6c64d4ba0065). The situation is similar for other lakes.

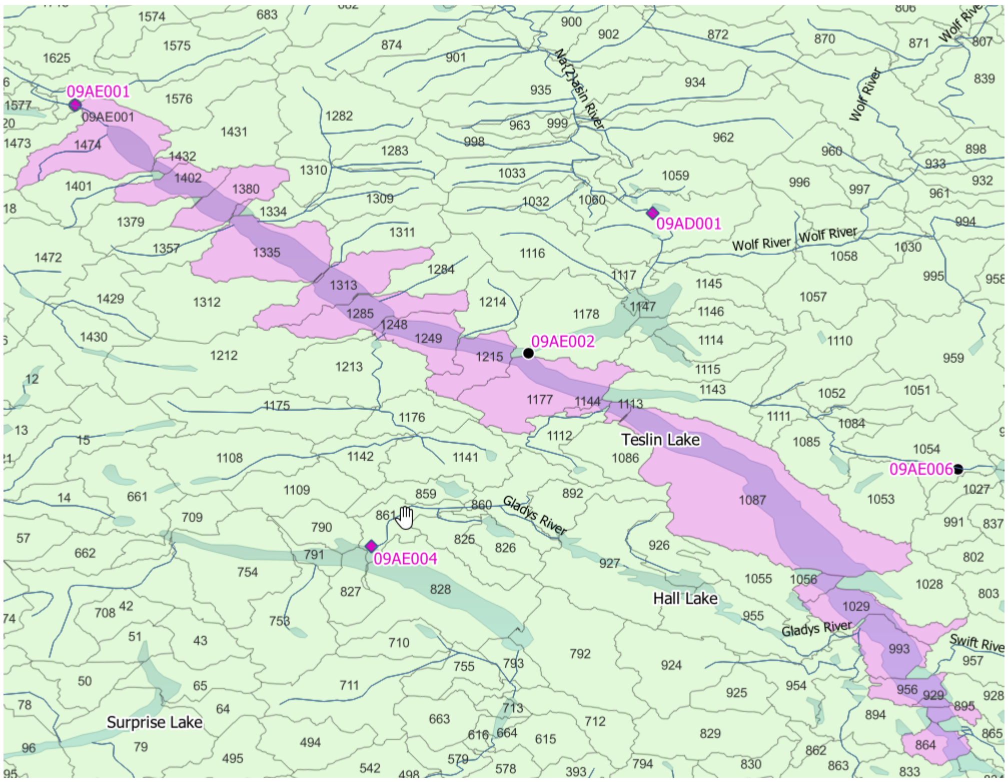


Figure 4 Designated sub-basins (magenta) that belong to Lake Teslin (Light blue) in the vector-based setup.

Lakes are modelled in MESH as special routing elements where runoff generated in all designated elements (grids or sub-basins) is collected without routing in addition to all inflows routed from other sub-basins draining into the lake, and then an outflow equation is applied at the lake outlet. The lake outflow equation is a relationship based on the lake storage volume and outflow discharge. Lake outflow equations were transferred from the grid-based setup as calibrated for GEM-CaPA and have not been revisited for this work as they still performed reasonably well. Lake levels are then produced by dividing the storage volume by the lake area. Given that lakes are not properly resolved, even using the actual lake areas from the Canadian Water Atlas does not result in proper levels. Therefore, in order to calculate level duration curves (LDCs; Figure 5) for the 9 lakes that are included in the setup (see Table 8 of Elshamy et al., 2020), adjustments for the lake area (dividing by the area x adjustment factor) and for the datum (additive adjustment) are needed to match the available level observations. This method is not applicable where there are no level observations and may be inaccurate where the level record is short. However, it shows potential that surpasses the simple nudging as done for forecasts, as it adjusts for the amplitude of the annual cycle. LDCs are to be used with caution due to the several caveats mentioned.

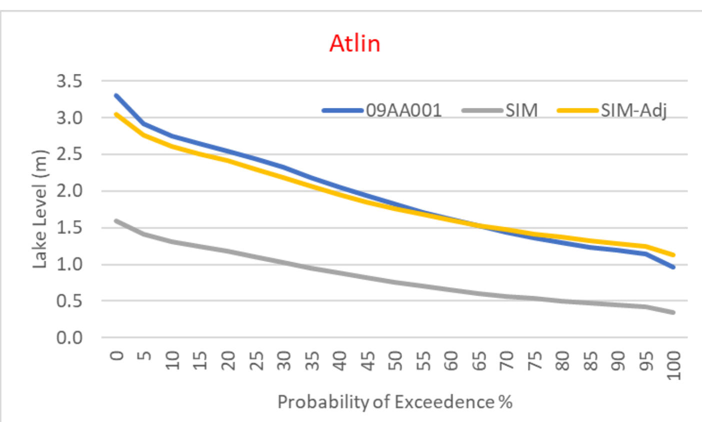
Table 4 Configured Lakes in the Yukon River Basin and their Area/Datum Adjustment Factors

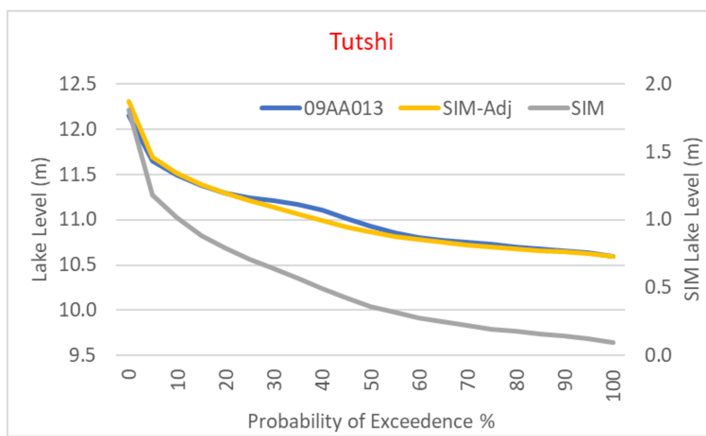
Lake	Area Adjustment	Outlet Gauge	Level Gauge	Datum Adjustment (m)	% Complete (level) [1980-2018]
Atlin	0.75	09AA006	09AA001	0.6	80.1%
Tutshi	1.00	09AA013	09AA013	10.5	20.2%
Tagish[1]	1.00	Fictitious	09AA017	4.0	54.2%
Marsh	0.25	Fictitious	09AB004	-0.6	98.8%
Schwatka[2]	5.80	09AB001	09AB001	-0.2	10.7%
Laberge	0.80	09AB010	09AB009	5.0	77.2%
Kluane[3]	0.70	09CA002	09CA001	2.0	69.3%
Teslin	0.75	09AE002	09AE001	2.0	96.0%
Kusawa	0.80	09AC004	09AC005	0.8	18.0%

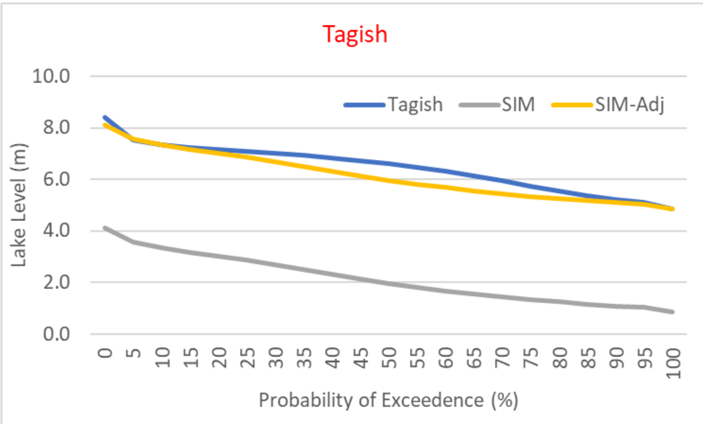
[1] Lake Tagish is combined with Lake Bennet (including Lindman), the area used is Tagish's including Fantail

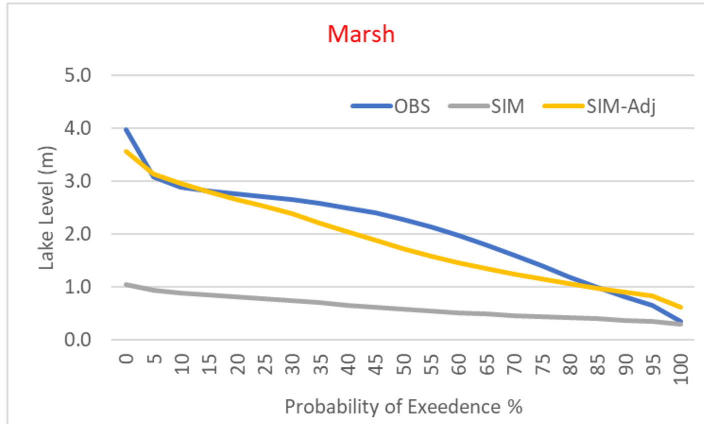
[2] Lake Schwatka is controlled by a structure on the outlet of Lake Marsh, the datum of the observations was changed on 1/1/2017.

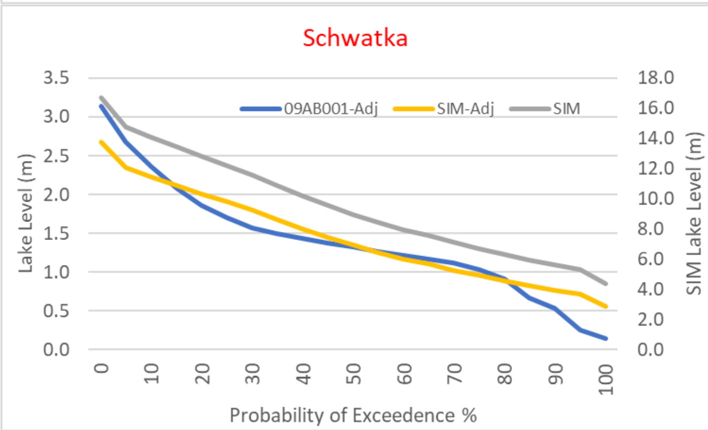
[3] Adjustments are based on the record up to the end of 2015 before the Kaskawulsh glacier changes to discharge to the Slims river which does not contribute to the lake (see Loukili and Pomeroy, 2018 for details).

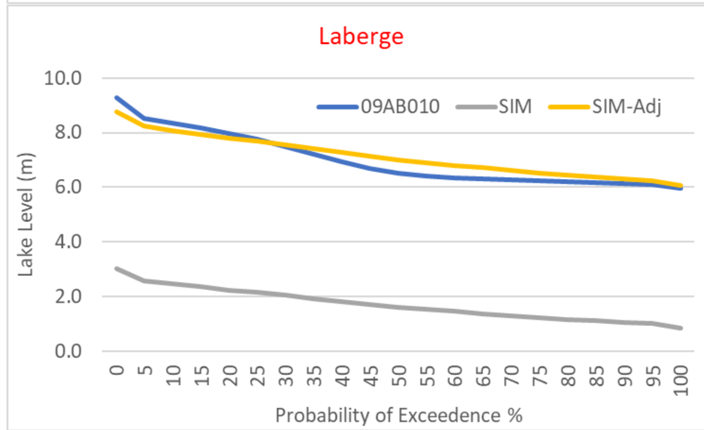


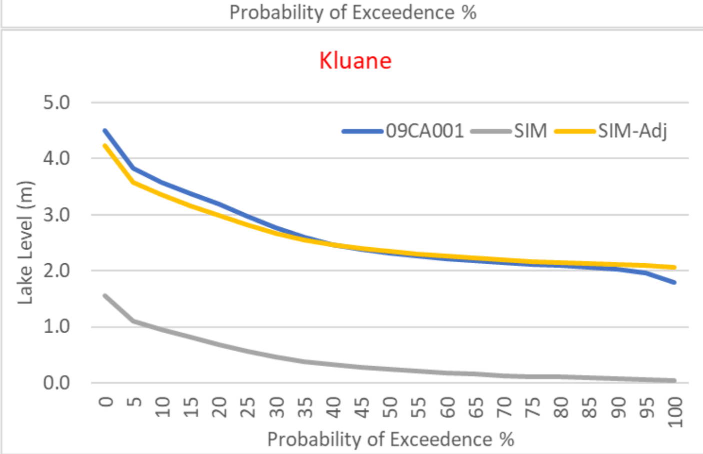


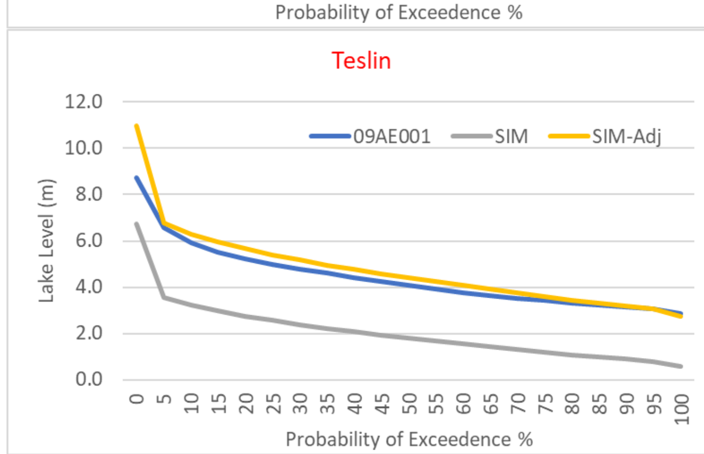












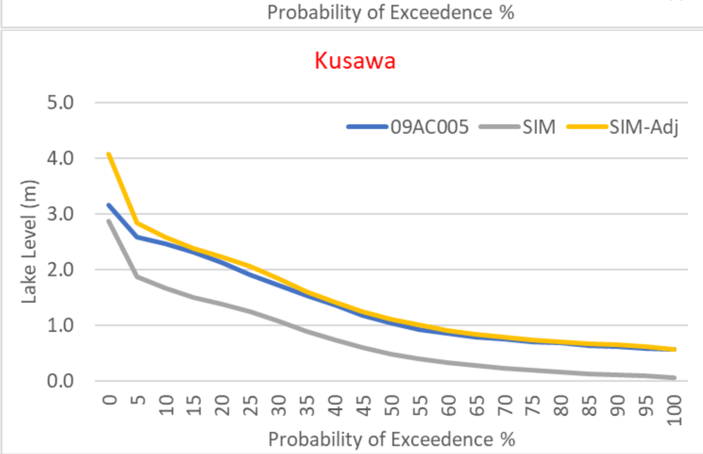


Figure 5 Level Duration Curves for configured Lakes in the Yukon River Basin. LDCs for observations are based on available records which vary per station – see Table 4

5. Assimilation of Snow Observations

The flow regime of the YRB and its tributaries is dominated by seasonal snow accumulation over the cold winter and spring melt. Although some flow peaks occur due to summer rainfall storms, streamflow peaks for most years occur due to snowmelt during the months of May and June. Therefore, the performance of MESH in simulating snow accumulation and melt rates is key to the accurate prediction of peak streamflow in the major rivers of the basin. The basin is sparsely covered with precipitation gauges and is not covered with weather radar, which diminishes the benefits of precipitation assimilation into the GEM-CaPA product. As a result, the seasonal winter precipitation can be the main source of snow accumulation errors. A simple method was tested here to adjust the cumulative winter precipitation from the start of the accumulation season based on the difference between the simulation and ground-based snow observations. Two types of snow observations were made available for this by the Yukon Government to test the approach. These include 6 snow pillow sites that provide a near continuous and real-time record of snowpack water equivalent at a point and 86 snow courses (some inactive) that provide areal snowpack water equivalent measurements at the beginning of March, April and May each year. This test employed the operationally used grid-based YRB setup forced by GEM-CaPA because it runs faster, is used by Yukon Environment and GEM-CaPA is the dataset used operationally to produce the forecasts. However, the method is applicable to the vector-based GC-MESH and could also be used to improve the performance for the historical simulations by RDPS-MESH as the data permits. To be able to assess the method, historical years were selected rather than adjusting 2022-2023, so as to be able to assess the impact of the adjustments made on the streamflow (2023 summer is yet to be observed) and on the snow water equivalent for full seasons.

The first application was done using Tagish snow pillow (09AA-M1) and snow course (09AA-SC010) – see Figure 6. First, the simulation results were extracted for the corresponding grid for two snow seasons (2007—2008 and 2008-2009) from Oct 1 to mid-June. Concurrently, the precipitation for the same grid cell and the streamflow for the nearest d/s station (09AB001 in this case) were extracted. Precipitation was accumulated starting from Oct 1. The model usually starts accumulating a snowpack before the snow pillow can detect it. This could be model error but could also be that snow pillows are not as sensitive when snow amounts are very small. Correction factors based on the Tagish snow pillow SWE and the model SWE at the end of Oct, Nov, Dec, Jan, Feb and Mar were calculated and used to adjust the precipitation progressively, rerunning the model forward each time from the beginning of the adjustment month. The next adjustment was based on the revised simulation. This resulted in improvement of the modelled SWE as shown in Figure 7. The first adjustment at the end of Oct (Adj1) overestimated the snow grossly but the next adjustments were generally inline with each other. The adjustment based on the end of Dec is the best followed by the one at the end of March. This means that adjusting using the end of Dec or Mar snow pillow observation could be sufficient in this case and the progressive adjustment could be simplified to one or two stages. The error metrics (RMSE) over the snow season were calculated for each adjustment as shown in Figure 8. The maximum reduction in RMSE occurred for the end of Dec adjustment (Adj3) and amounted to 49% compared to the original simulation. The streamflow at the nearest d/s station (09AB001 in this case) showed some deterioration because the Tagish snow pillow station is not close enough to parts of the basin (i.e., it may not be fully representative of the sub-basin) and is affected by Marsh Lake outflows. There are other snow course and pillow data in the region so assuming that the same adjustment applies everywhere could have caused errors.

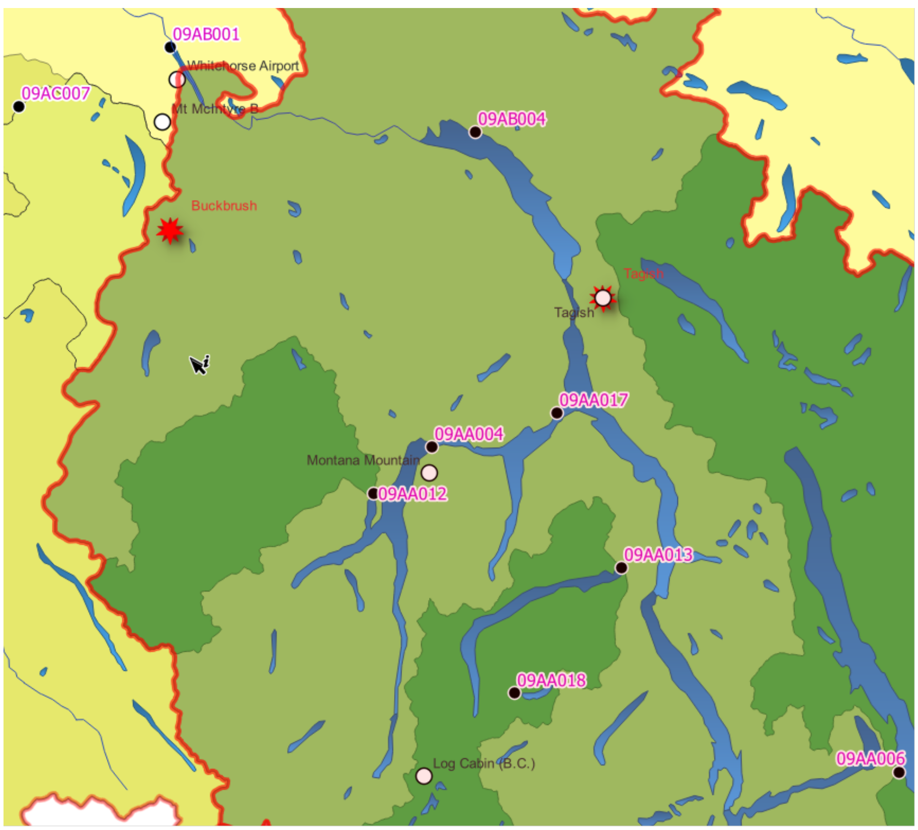


Figure 6 Snow Pillow (red stars) and Snow Course (white circles) sites in the Upper Yukon. Streamflow gauges are shown as black circles with red labels.

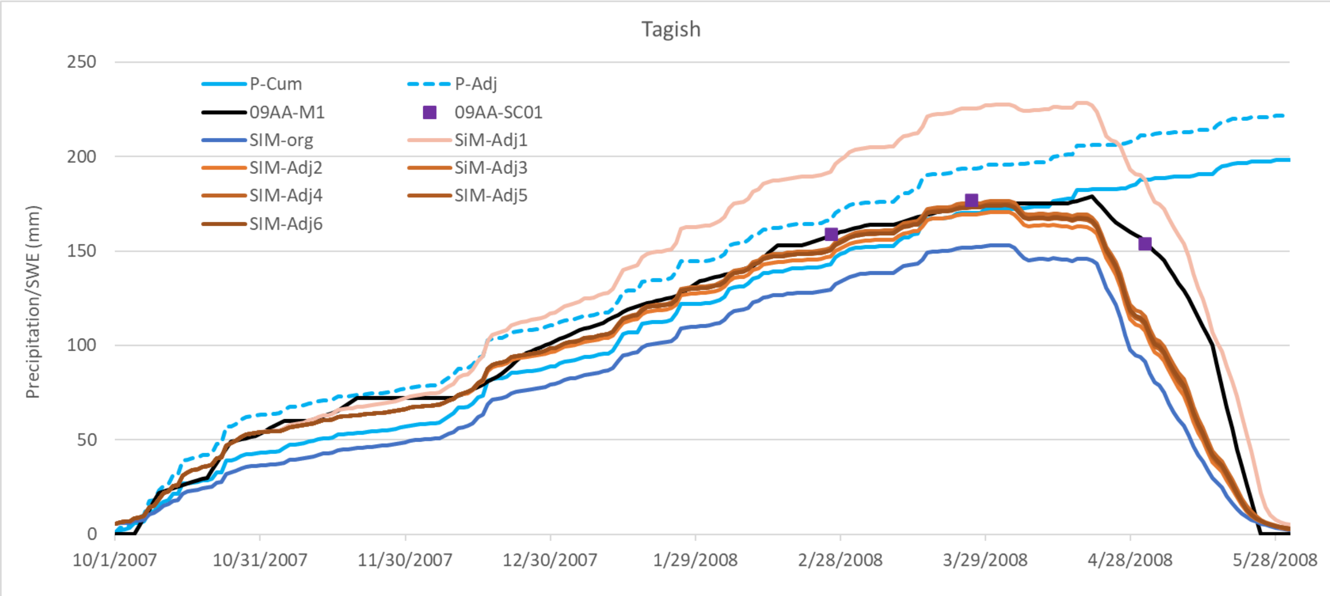


Figure 7 Progressive Adjustment of Precipitation to Assimilate Snow Pillow Observations at Tagish (09AA-M1) for 2007-2008. Adj1 - 6 are made based on SWE at the end of Oct, Nov, Dec, Jan, Feb, and Mar respectively.

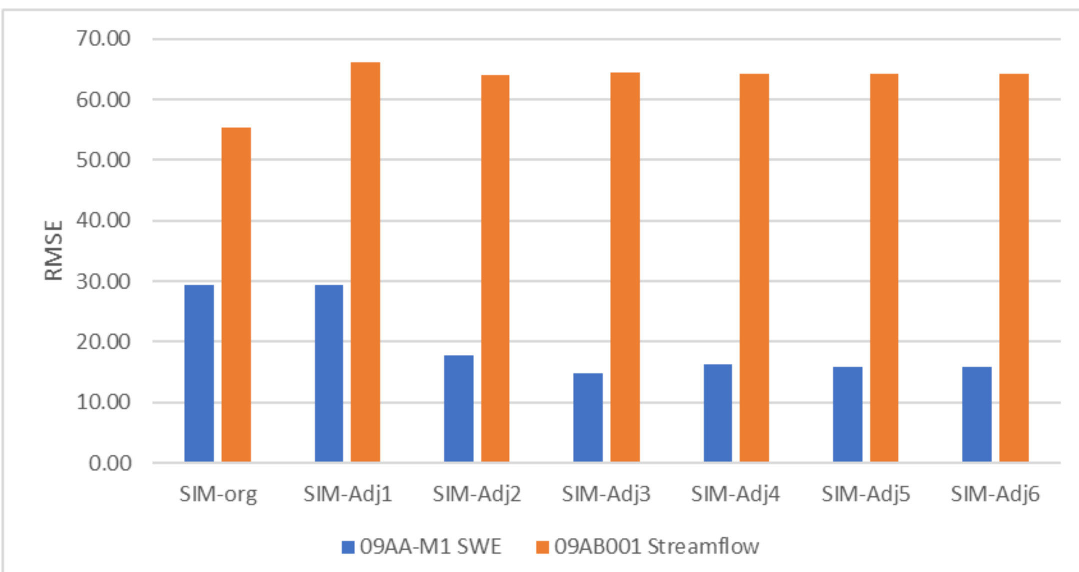


Figure 8 RMSE for the 2007-2008 SWE Assimilation Simulations at Tagish

Such a progressive adjustment is only possible at the few sites with daily snow pillow data. To examine how monthly snow course information could be assimilated, the numerical experiment was repeated assuming that only the snow course data at the beginning of March, April and May is available – so in this case the snow pillow data was used only to assess model performance and was not assimilated. The May snow survey occurs during the snowmelt period and so was excluded from analysis, leaving two progressive adjustments, one based on the March and one on the April snow surveys. Figure 9 indicates that adjusting based on March survey is slightly better and RMSE is reduced by 60% in such case, which is better than the progressive adjustment based on the Snow pillow data shown above.

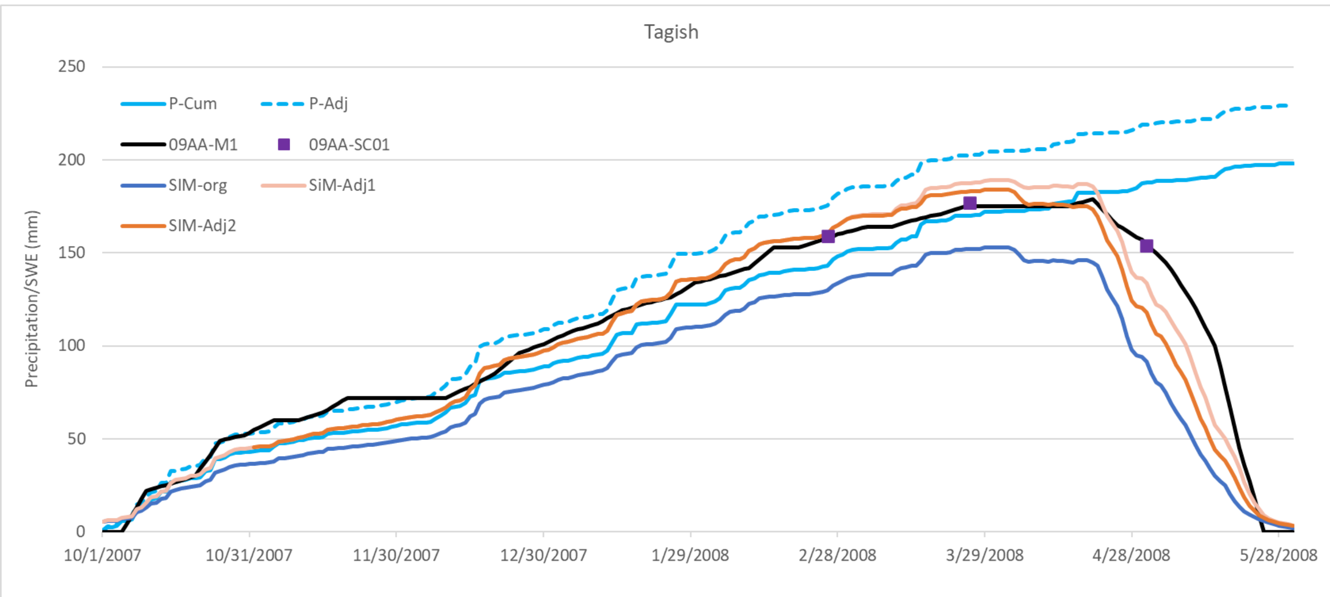


Figure 9 Progressive Adjustment of Precipitation to Assimilate Snow Course Observations at Tagish (09AA-SC01) for 2007-08. Adj1 and 2 are made based on SWE at the beginning of March and April respectively.

The procedure was repeated at Tagish for the year 2008-2009 using the snow course data (Figure 10). For this year, the snow pillow data stops on April 28 and therefore the error metrics are only calculated until that date. Unlike 2007-08, the snow course data deviated a bit for the April survey compared to the snow pillow data. However, adjusting the precipitation using the March survey improved the quality of the snow simulation (58% error reduction). Further adjustment using April survey did not improve this further.

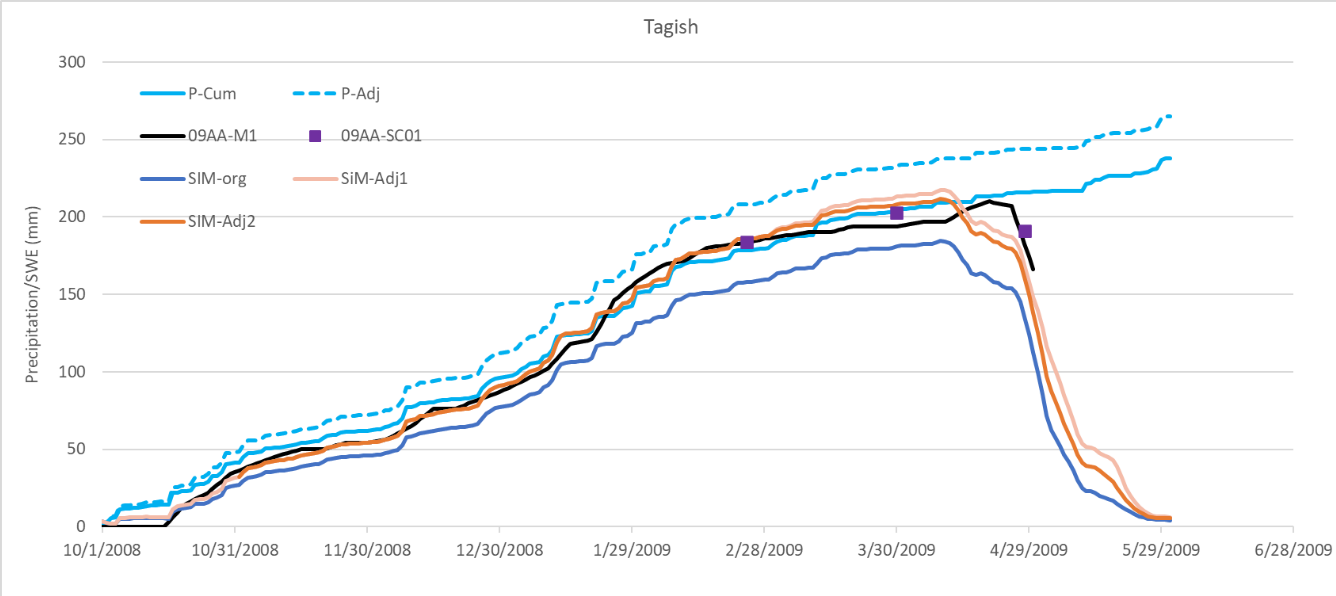


Figure 10 Progressive Adjustment of Precipitation to Assimilate Snow Course Observations at Tagish (09AA-SC01) for 2008-09. Adj1 and 2 are made based on SWE at the beginning of March and April respectively.

From this, the approach showed good applicability based on snow course data which is more widely available in the basin. Thus, a final test was made at a different location. For that last test, The Grizzly Creek snow course was selected (Figure 11), paired with the streamflow at 09EA004 (North Klondike near the mouth) to assess the impacts of the corrections as there are no snow pillow site in that sub-basin. As this site is in northern Yukon, snowpacks start to accumulate earlier and melt later than at Tagish. Therefore, Sep 1 was chosen as the start of the accumulation period for the selected year (2005-2006). Using the March survey to adjust the precipitation resulted in fitting the April and May surveys well and further corrections were not made (Figure 12). The flow at the next d/s station improved significantly as shown in Figure 13 (left). For this situation, snow was overestimated in the original model run, and this resulted in overestimating the discharge on June 17, 2006. Assimilation of SWE at Grizzly Creek reduced this overestimation significantly. RMSE of the flow simulation over the whole period (Sep 1 to Jun 30) was reduced by 29%. However, further downstream at 09EA003 (Klondike above Bonanza Creek), the simulation deteriorated (Figure 13 (right)), as other tributaries join the river below 09EA004 and snow may need to be adjusted differently for those sub-basins. Possibly assimilating SWE data from King Solomon Dome (09EA-M1 and 09EA-SC01) could improve the results further.

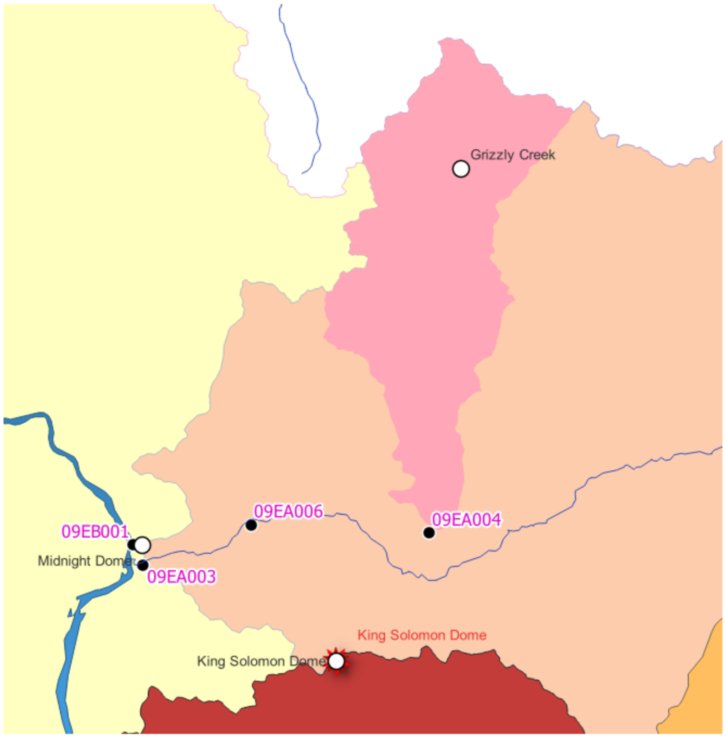


Figure 11 Snow Data for the Klondike sub-basin, same symbols are as in Fig. 6

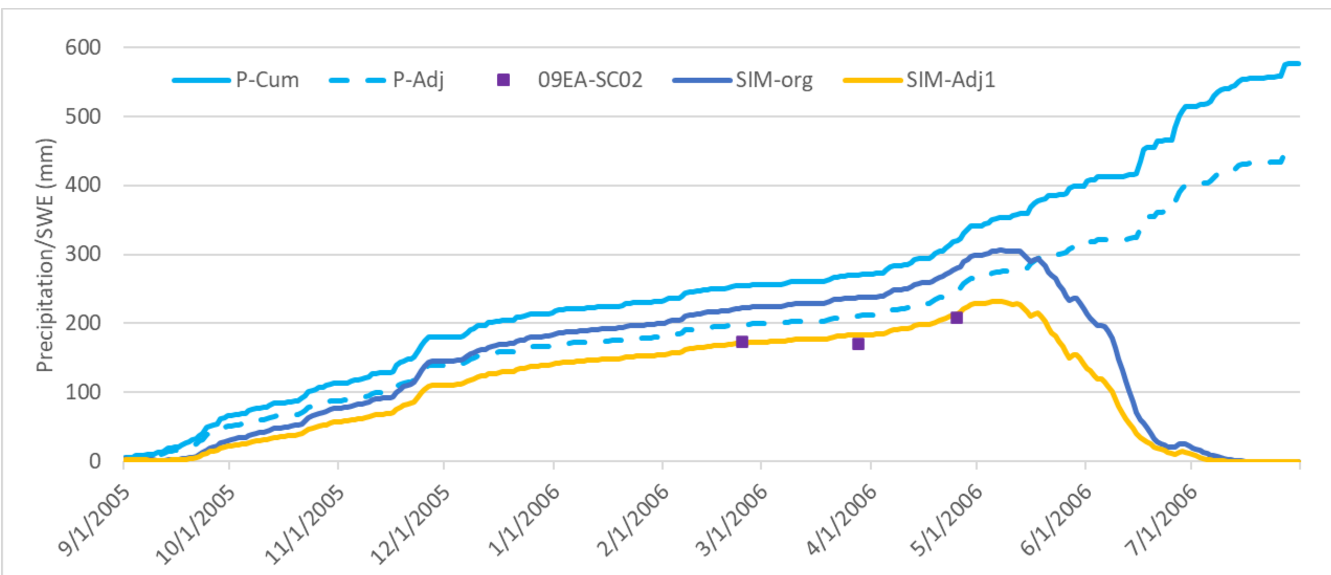
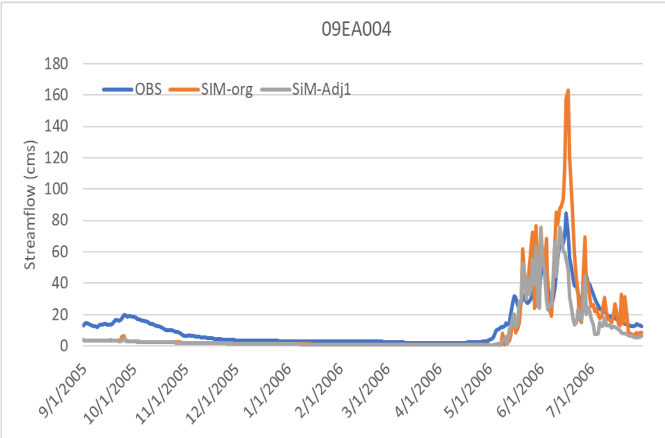


Figure 12 Assimilation of Snow Course data at Grizzly Creek for 2005-2006



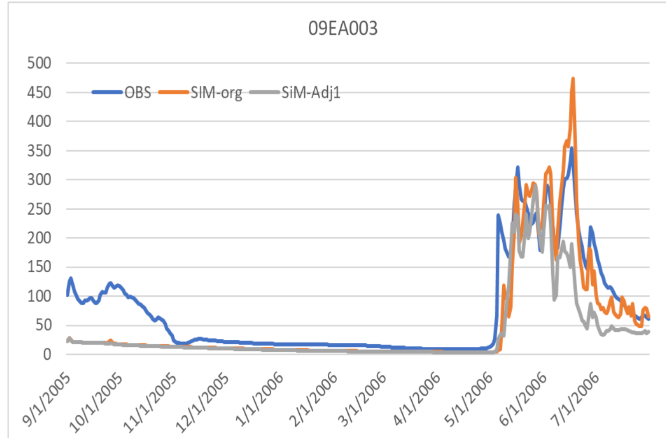


Figure 13 Impact of Snow Assimilation of Grizzly Creek on downstream streamflow (2005-2006)

To integrate the snow assimilation procedures for forecasting purposes, using the March snow survey data is likely to be sufficient. The procedure can thus be done well ahead of the mid-April start of the forecast season using model simulations of the past winter (starting in September). Comparing the model SWE to observations, correction factors can be calculated and applied to precipitation and the model can then be rerun to calculate the adjusted SWE states, as well as other states. These initial conditions can then be used for the forecast simulations. Checks for SWE based on April and May surveys can then be performed and further adjustments can be made is needed. The adjustment factors need to vary spatially and thus an areal mask needs to be created assigning each snow station (course/pillow) to a certain region/sub-basin for which to apply the factors. Currently, MESH allows a uniform adjustment factor to precipitation and thus the spatially varying adjustments will need to be applied before the precipitation is passed to MESH to run the model. This procedure can be generalized to other setups including the vector-based ones and the 5k ones.

6. Conclusions and Recommendation

A vector-based model discretization and routing setup for the MESH model of the Yukon River basin has been revised and calibrated to both GEM-CaPA and RDRS v2.1. The Vector-based MESH performance was initially slightly inferior to those of the grid-based discretization when parameters were transferred directly. However, calibration improved the performance significantly, especially under the RDRS v2.1 dataset. A long-term simulation using the RDRS v2.1 data was performed for the period 1980-2018 and was used to produce flow and level duration curves at selected stations. The simulated Flow/level duration curves compared favourably to observation-based ones when the observed records had few gaps. FDCs can be produced at any location in the basin. However, LDCs can only be produced for the configured lakes as the simulated levels have to be adjusted to match observations (based on available records). Lakes are poorly resolved and therefore LDCs should be used with extreme caution.

Additionally, a new procedure for snow data assimilation to improve snow and streamflow prediction has been developed and tested at a few locations as a proof of concept. Assuming that the error is the accumulated snow originates from overestimation or underestimation of precipitation, the precipitation has been adjusted based on the available snow course/pillow data and an initial seasonal simulation. Adjustments based on the March snow surveys seemed to produce the greatest improvement in snow simulations as well as for streamflow, in situations where the basin gauged by the streamflow gauge includes the area near the snow course/pillow site. Further refinement of the procedure is necessary to include spatially variable adjustments based on a mask assigning each snow station to a representative region.

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