A Distributed Hydrological Modelling System to Support Hydroelectric Production in Northern Environments under Current and Changing Climate Conditions

Progress Report presented to :

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The staff at YEC represents one of the driving forces behind this project, thus, we would like to acknowledge their strong contributions towards the achievement of the different project objectives (a.k.a., work packages).

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Summary

The objective of this project is to implement a distributed hydrological modeling system on key watersheds of the Yukon Energy Corporation (YEC). This system will be used for hydrological forecasting (*i.e.*, inflows and stream flows) with different lead times (*e.g.*, 1-14 days) to assist hydroelectric operations as well as seasonal and long-term planning. Long-term planning will use the modeling system to predict impacts of climate change on inflows and flow availability, timing and extreme events. The results will provide strategic information for the assessment of potential energy projects to supply Yukon with enough electricity to meet projected demands. Understanding climate change and associated effects will be useful to other processes such as relicensing activities. This progress report provides a brief description of the state of the work packages (WPs) conducted over the course of the first year of this project study and highlights the tasks to be conducted over the next year.

List of acronyms

ARD	Applied Research and Development
BC	British Columbia
CanSIPS	Canadian Seasonal and Inter-annual Prediction System
CaPA	Canadian Precipitation Analysis
CGCM	Canadian General Circulation Model
CMIP5	Coupled Model Intercomparison Project Phase 5
CRD	Collaborative Research and Development
DA	Data Assimilation
DEM	Digital Elevation Model
ECCC	Environment and Climate Change Canada
EnKF	Ensemble Kalman Filter
ENSO	El Niño Southern Oscillation
ESP	Ensemble Streamflow Prediction
GDPS	Global Deterministic Prediction System
GEPS	Global Ensemble Prediction System
GIS	Geographic Information System
GUI	Graphical user interface
HQP	Highly Qualified Personnel
INRS	Institut National de la Recherche Scientifique
IPCC	Intergovernmental Panel on Climate Change
MDDELCC	Ministère du Développement Durable, de l'Environnement et de la Lutte aux Changements Climatique
NAEFS	North American Ensemble Forecast System
MSC	Meteorological Service of Canada
NCE	Northern Climate ExChange

NSERC	Natural Sciences and Engineering Research Council of Canada
PCIC	Pacific Climate Impacts Consortium
PDO	Pacific Decadal Oscillation
RCPs	Representative Concentration Pathways
RDPS	Regional Deterministic Prediction System
RHHU	Relatively Homogenous Hydrologic Units
RFS	River Forecasting System
RSs	River Segments
SWE	Snow Water Equivalent
SVD	Singular Value Decomposition
SVM	Support Vector Machine
WP	Work package
YC	Yukon College
YEC	Yukon Energy Corporation

Context

In northern environments, limited hydro-meteorological networks and evolving climate conditions provide continuous challenges to water resource managers. YEC operates hydroelectric facilities under such conditions. For long-term resource planning exercises where capacity and predicted electrical load are analyzed to inform new projects, YEC does noes not currently factor in climate variability and change. Thus, there is a fundamental need to: (i) establish detailed knowledge of current and future hydro-meteorological conditions and (ii) assess the sensitivity of each hydroelectric facility to climate.

To address these issues, YEC has recruited a multidisciplinary team of hydrology and climate change experts to jointly undertake an applied research project under NSERC Applied Research and Development (ARD) and Collaborative Research and Development (CRD) Programs. This research team includes members from the Northern Climate ExChange (NCE, part of the Yukon Research Centre at Yukon College), Institut national de la recherche scientifique (INRS, Quebec) and Ouranos (Consortium on regional climatology and adaptation to climate change, Quebec).

The team of experts is currently developing a hydrological modeling framework using existing data and providing context-specific studies and model advancements, tailored for northern environments, using a combination of field studies and cutting-edge data assimilation techniques. For NCE, the primary focus will be to develop an innovative data assimilation tool that YEC can use to perform accurate short-to-medium-term inflow and flow forecasting (daily and up to 1-year lead) and to optimize operational reservoir monitoring and management. Other tasks relate to providing support to the CRD project proposed by INRS (e.g., bias correction of weather forecast products; snow survey data). For INRS and with the collaboration of Yukon College, the focus will be on implementing a robust, distributed, hydrological modelling system for short-term (1-14 days) predictions (i.e., inflow and streamflow forecasting), seasonal projections (1-12 months) and long-term hydrological trends (30-year time periods, e.g., 2040-2070). NCE will use the forecasting framework provided by INRS to develop the aforementioned data assimilation tool. INRS will provide training to YEC professionals (operation of the inflow and streamflow forecasting system) and highly qualified personnel (HQP) to conduct research in northern hydrology and build the professional and technological capacities of YEC.

1. Introduction

Inflow and streamflow forecasts have proven to be of value for the operations of hydropower systems in Canada. Forecasts are often use with the dual purpose of maximizing energy production while providing flood control. For example, Hydro-Quebec and BC Hydro use forecasts to optimize hydropower system operations (Schaffer and Shawwash, 2014; Gignac et al., 2014; Martin et al., 2014) while Rio-Tinto Alcan operates hydroelectric plants to supply energy to aluminum smelters in Quebec and British-Columbia (Larouche et al., 2014). Both utility companies operate plants in northern environments where snowmelt represents a major hydrologic process. Meanwhile, the Quebec Ministry of Sustainable Development, Environment and Climate Change (MDDELCC) uses inflow forecasts to manage a considerable number of dams affected by significant spring freshets, several of them requiring real-time management (Turcotte and Lafleur, 2014). Uncertainty associated with the monitoring of snow water equivalent (SWE) and spatial distribution of snowpack adds complexity to forecasting the timing and volume of the spring freshet. YEC faces equivalent challenges in the operation of three hydroelectric dams, the Whitehorse, Aishihik and Mayo Facilities. The impacts of climate change on watershed hydrology, glacier dynamics and permafrost provide additional uncertainty when there is a need to asses long-term hydrological trends (30-year time periods, e.g., 2040-2070). YEC has recognised the need to account for climate change in the planning, management and relicensing (25-year license) of hydroelectric reservoirs. For YEC, there is also a need for basic short-term as well as mid-term seasonal forecasts. This latest requirement is in line with the need to support water resources mangers with environmental predictions with forecast ranges from 2 weeks to 12 months (National Academies of Sciences, Engineering and Medicine, 2016).

Hydrological forecasting requires the use of weather forecasts as inputs to a hydrological modelling system. Fort short-term forecasts, data assimilation techniques based on post-processing of model outputs or adjusting model inputs, state variables or parameters, are generally used to improve forecasts. For short lead times, weather forecasts are usually deterministic, while they are probabilistic (i.e., ensemble forecasts) for longer lead times (e.g., Thirel et al., 2008). Sene (2010) reports knowledge of correlations between large-scale atmosphere and oceanic structures (e.g., Pacific Decadal Oscillation, PDO, El Niño Southern Oscillation, ENSO) may be useful for long-term forecasts.

Furthermore, demand forecasts for energy supply along with reservoir/lake level constraints and/or downstream flow regulations, may then be used as inputs to an existing reservoir management model.

The overarching goal of this project is to implement a distributed hydrological modelling system to support hydroelectric production in Yukon under current and changing climate conditions. Building from previous collaboration between NCE and YEC, the project increase the capacity for short and mid-term inflow forecast for the Mayo, Aishihik and Withehorse Facilites and assess potential change in flow volume and extreme events due to climate change in terms of severity, timing and frequency more specifically for Mayo and Aishihik Facilities. To achieve these goals, model advancements, tailored for northern environments, will require development or adaptation of permafrost, multi-layer snow and glacier modules, using a combination of field and theoretical studies. Environment and Climate Change Canada (ECCC) products (i.e., observed and weather forecasts, streamflows) and different sources of reanalysis data and climate projections supplied by Ouranos will be used for calibration and operation of the hydrological modelling system. It will also require the development of a methodology to link inland precipitation and temperature conditions to large-scale circulation indices using climate model data along with historical data.

This progress report presents the state of the different work packages of the project under specific chapters, namely Chapter 2, implementation of a distributed hydrological modelling system for short and mid-term forecasts; Chapter 3, implementation of permafrost and multilayer snow modules; Chapter 4, development and/or adaption of a glacier module for the Upper Yukon River watershed; Chapter 5, development of a methodology to link regional precipitation and temperature with large-scale circulation indices; and Chapter 6, assessment of long-term changes in flow volume and timing, and extreme events due to climate change (i.e., hydroclimatic assessment). Each chapter includes the supporting literature, the proposed methodology and preliminary results when applicable.

2. Distributed hydrological modelling and forecasting system

2.1. General methodology and supporting literature

Operational hydrological models for forecasting inflows, stream flows, and extreme flows (floods or droughts) are conceptual, distributed or data-driven models. For example, Sene (2010) reported that the BC Hydro River Forecasting System (RFS) relies on the semi-distributed UBC Watershed Model (Quick, 1995). Five-day inflow forecasts are issued for several reservoirs using a daily time step which can be switched to hourly when required. For operational purposes, BC Hydro uses lead times varying between two days and nearly 10 days. For longer lead times (*i.e.*, seasonal), BC Hydro uses an Ensemble Streamflow Prediction (ESP) framework based on weather forecasts or climate data (*i.e.*, historical). Such forecasts are very important, since the spring freshet represents a major portion of the annual water supply. Hence, for northern watersheds, assimilation of SWE becomes an essential key feature of any forecasting systems. Other deterministic models currently used by operators of hydroelectric facilities or river forecasting centres include: (i) the lumped models SAC-SMA (Finnerty et *al*., 1997; Burnash, 1995) coupled or not with SRM (Martinec, 1975; Abudu et *al*., 2012), SLURP (*e.g.*, Su et *al*., 2000) and HSAMI (Bisson and Roberge, 1983; Fortin 2000); (ii) the semi-distributed models HBV (Lindström et *al*., 1997, Sorman et *al*., 2009), HEC-HMS (Anderson et *al*., 2002), WATFLOOD (Kouwen et *al.*, 2005) and HYDROTEL (Fortin et *al.*, 2001; Turcotte et *al.*, 2003, 2007; Fossey et *al.*, 2015); and (iii) the distributed model HL-RDHM (Koren et *al*., 2004), to name a few.

This section presents the implementation of a forecasting system for short- and mid-term lead times using HYDROTEL as the core hydrological model. HYDROTEL developed at INRS, in collaboration with Hydro-Quebec, is supported by the project research group. HYDROTEL is currently used for inflow and hydrological forecasting of publicly-owned dams in Quebec (Turcotte et al., 2004).Since YEC does not have any experience in operating an inflow forecasting system, a multimodel approach (*e.g.*, Oudin et *al.*, 2006, Kayastha et *al.*, 2013, Sellier et *al.*, 2012) is beyond the scope of this project.

From a hydrological modelling perspective, the model simulates evapotranspiration, snow accumulation/melt, soil temperature/freezing depth, infiltration, recharge, surface flow, subsurface flow and channel routing; using an intra-daily (*i.e.*, 1, 3, 6, 12 hr) or a daily time step.

Hydrometeorological data include gridded or site-specific precipitation, maximum and minimum air temperatures; and for model calibration, stream flows and any other relevant state variables (*e.g.*, SWE). The computational domain is made of interconnected river segments (RSs) and either three-soil-layer sub-watersheds or hillslopes, referred to as relatively homogeneous hydrological units (RHHUs). The latter units are defined using PHYSITEL, a specialized geographic information system (GIS) (Turcotte et *al.*, 2001; Rousseau et *al.*, 2011; Royer et *al*. 2006) for the determination of the complete drainage structure of a watershed using a Digital Elevation Model (DEM) and digitized river and lake networks. Additional characterization of the watershed by PHYSITEL requires integration of a classified land cover map, soil texture map based on percentage of sand, loam, and clay, along with corresponding hydrodynamic properties (Rawls and Brakensiek, 1989), and wetland attributes.

Implementation of HYDROTEL for short- and mid-term forecasts at YEC is being achieved by using a customized Graphical User Interface (GUI) developed at INRS. The system which is developed in collaboration by INRS and NCE accomplishes the following tasks: (i) updating and formatting of observed meteorological data; (ii) updating and formatting of monitored SWE data and scaling on a weather forecast grid; (iii) updating and formatting monitored water levels and flows and calculating recent reservoir inflows; (iv) downloading the North American Ensemble Forecast System (NAEFS) issued by the Meteorological Service of Canada (MSC) for the 1 to 14 days weather forecast; (vii) formatting and correcting of weather forecast data compatible with HYDROTEL; (ix) adjusting values of state variables (as initial conditions for forecast simulation) with data assimilation; (x) for specific time of the year, adjusting values of weather data; (xi) data assimilation of SWE; using HYDROTEL to generate hydrological forecasts; and (xiii) sharing of hydrological forecasts for the target lead time. Along the process NAEF requires bias correction using tools developed by NCE.

For longer lead times (*i.e.*, seasonal inflow forecasts; 1 to 12 months), an ESP framework based on weather forecasts is available. The current framework includes: ECCC's seasonal forecasting system CanSIPS (Canadian Seasonal and Inter-annual Prediction System, Merryfield et *al.*, 2011), which relies on the Canadian General Circulation Model (CGCM) producing forecasts for up to one year, performed every month (*i.e.*, 20 members, monthly mean for each member). It is noteworthy that beyond the first month, most seasonal weather forecasts have low skill scores for precipitation; that is why ensuing hydrological forecasts have limited reliability. For large northern watersheds, seasonal weather forecasts could be valuable for assessing the effect of a warming trend on snowpack and spring freshet dynamics. Nevertheless, downscaling issues related to spatial and temporal resolutions associated with CanSIPS will be downscaled and disaggregated for the watersheds studied by NCE which has experience in the subject matter.

Yukon Geomatics public portal, British Columbia (BC) geomatics portal and ECCC represent the major data providers for the development of the hydrological forecasting system. The required data include: physiographic information (30-m horizontal & 5-30-m vertical resolutions DEM), land cover (2005 MODIS and 2000 CIRCA Canadian Land Cover Classification 2005 MODIS and 2000 CIRCA Canadian Land Cover Classification and Alaska National Land Cover Database, 250-m to 30-m resolution), soil texture (Canadian soil texture map for percentage of sand, silt and clay (Szeto et *al.*, 2008), weather and climate data. Because of an upcoming relicensing constraint (December 31, 2019), the Aishihik watershed was modelled first, followed by the Mayo watershed and the Upper Yukon River watershed. For model calibration, reanalysis data (precipitation and minimum and maximum temperature) available on a 10-km grid such as the Canadian Precipitation Analysis (CaPa) (Fortin et *al*., 2014, 2015) and ANUSPLIN (Hutchinson et *al.*, 2009), could also be of interest for further calibration efforts. Several studies have relied upon reanalysis datasets in Northwestern Canada, for examples: (i) NCEP/NCAR (Kalnay et *al.*, 1996) have been used for studies in BC, southern Yukon, and Yukon River basin (Cannon and Whitfield, 2002; Pinard et *al.*, 2009 Rawlins et *al.*, 2006); (ii) NARR (Mesinger et *al.*, 2006) for glacier modeling in BC and Yukon River basin (Jarosch et *al.*, 2012; Ainslie and Jackson, 2010; Semmens et *al.*, 2013); and (iii) ERA-40 (Uppala et *al*., 2005) for several studies as well (Cassano and Cassano, 2010 Kerkhoven and Gan, 2011; Pointras et *al.*, 2011]. For this project, recent reanalysis datasets such as CFSR (Saha et *al.*, 2010), ERA-Interim (Dee et *al*., 2011), MERRA2 (Rienecker et *al*., 2011], JRA55 (Kobayashi et *al*. 2015) were considered for the calibration and validation process.

2.2. Integration of the studied watersheds into HYDROTEL

This section introduces: (i) the discretization of the Mayo, Aishihik and Upper Yukon Watersheds using PHYSITEL including presentation of the input data and construction of the ensuing database for the hydrological modelling; (ii) the importation of the database into HYDROTEL followed by model calibration, and (iii) the development of the inflow forecasting system.

2.2.1. Input data

Table 2.1 presents the information required for hydrological modelling of the study watersheds using the HYDROTEL/PHYSITEL modelling platform.

Table 2.1 Spatial data for watershed discretization using PHYSITEL

Input data	Available source
Digital elevation model (DEM)	Geomatics Yukon Natural Resource Canada
Stream and lake networks	Geomatics Yukon and DataBC geomatics portal
Land Cover	Natural Resources Canada Geomatics Yukon, United States Geological Survey
Soil Type (Texture)	Environment Canada Geomatics Yukon

Additional data required for hydrological modelling include: (i) meteorological data measured at different existing stations or reconstructed and distributed on grid; (ii) measured streamflow data at any location on the stream network or reconstructed reservoir inflows based on water level variation and known reservoir outflow or river flow. Other data source such as reanalysis data (precipitation and minimum and maximum temperature) CFSR (Saha et *al.*, 2010), ERA-Interim (Dee et *al*., 2011), MERRA2 (Rienecker et *al*., 2011], JRA55 (Kobayashi et *al*. 2015) were tested through the calibration process. Although other reanalysis data available such as CaPA (Fortin et *al*., 2014, 2015) and ANUSPLIN (Hutchinson et *al*., 2009) could also be of interest if required.

DEM

For all watersheds, the DEMs were created with 30-m resolution data sheets obtained from the Geomatics Yukon file transfer protocol (ftp) site (ftp.geomaticsyukon.ca/DEMs/) and Natural Resources Canada ftp site. In both cases, we used the ArcMap Mosaic tool to generate complete DEMs. Each data sheet was identified given coarse watershed limits available on the Geomatics Yukon site or roughly defined by INRS for the Upper Yukon River watershed. As a reminder, DEM data for Canada are commonly interpolated from the digital 1:50,000 Canadian National Topographic Database (NTDB Edition 2). The resulting DEMs will be introduced with the stream and lake network of each watershed.

Stream and lake networks

Each watershed stream and lake networks were extracted and built using the 1:50,000 watercourse and water body files available at the Geomatics Yukon and DataBC portal. The downloaded files were readily compatible with HYDROTEL, thus, precise data processing steps were taken to create satisfying networks. The following steps were achieved using the Arc Map tool:

1. For all watersheds, only streams and lakes within watershed boundaries were selected and those remaining removed. It is noteworthy that the watershed limits were reassessed to make sure that all streams and lakes contributing to the watershed outlet were carefully identified.

2. All isolated lakes – those not having any connection to the river network - were identified and removed.

3. Since really small lakes can generate errors during the integration process, all lakes covering less than 0.0144km² were removed and replaced by small river segments.

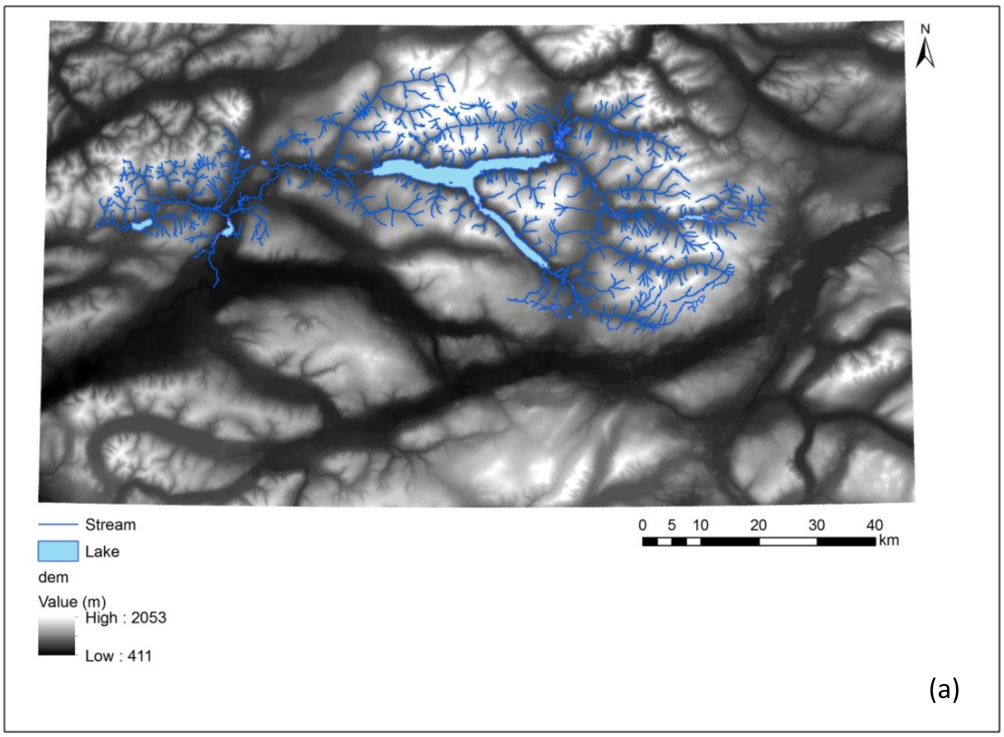
4. Since lakes are delineated by water bodies (polygons), large streams depicted as waterbodies using left and right banks were replaced with a single centerline watercourse.

5. All stream segments were properly connected together and when required connected to a lake contour vertex (point that defined the lake contour).

6. Using the MapInfo software, the stream network and the lake network were merged to provide a unique network for subsequent importation in PHYSITEL except for the Upper Yukon River watershed where rivers and lakes were used separately in a newer version of PHYSITEL.

7. Use of PHYSITEL provided a mean to identify any remaining errors in each stream and lake networks. PHYSITEL highlighted lakes with multiple outlets or small rivers that were fully contained within one tile of the DEM. These errors were rectified using PHYSITEL to ensure that the stream and lake networks were fully compatible with HYDROTEL.

Figure 2.1 presents the DEM and the stream and lake networks of the Mayo, Aishihik and Upper Yukon watersheds. Note that DEMs cover larger areas than those of each watershed.



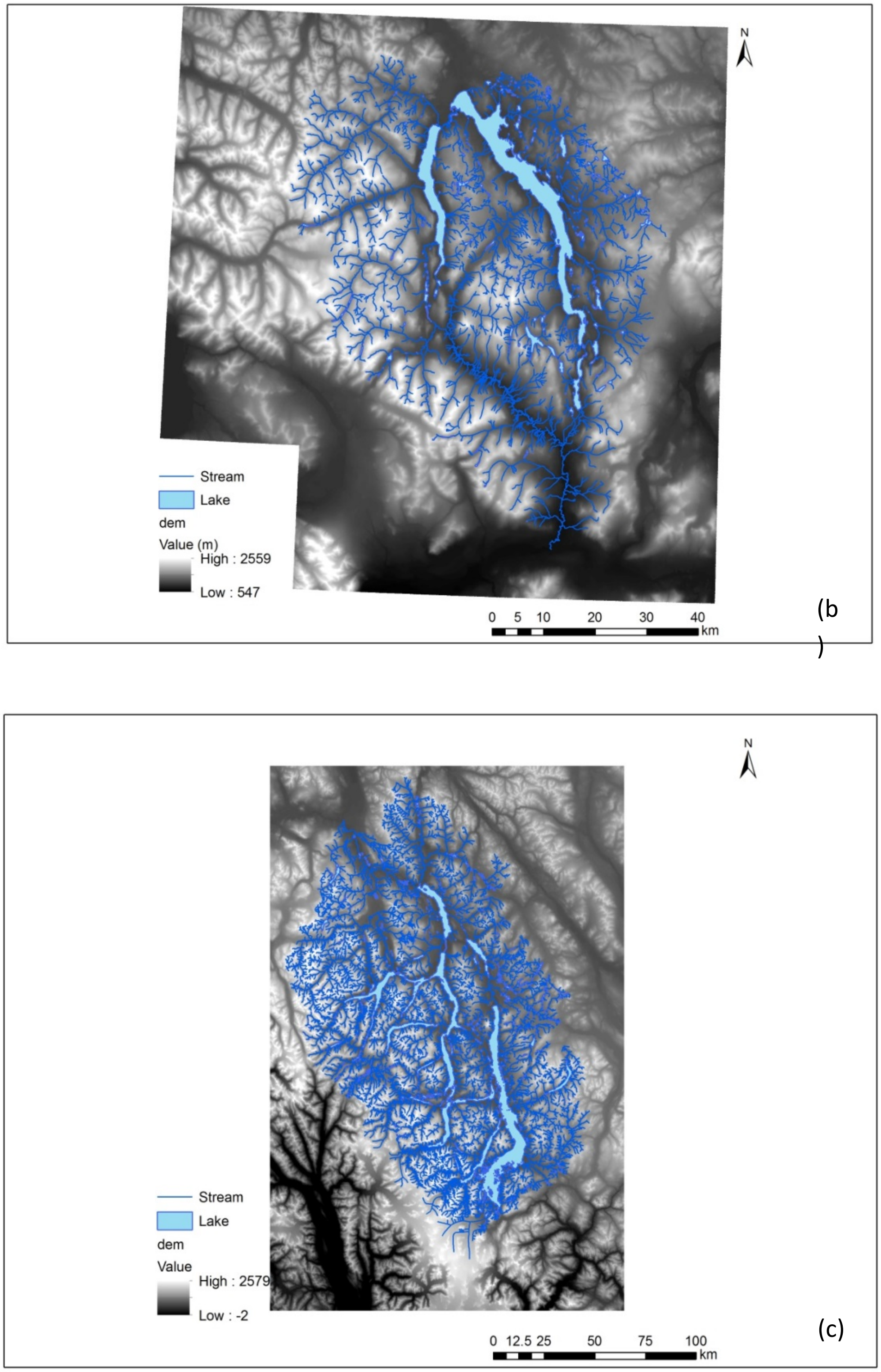


Figure 2.1 DEMs and stream and lake networks: (a) Mayo Watershed (b) Aishihik Watershed and (c) Upper Yukon River watershed.

Figure 2.1 illustrates that the each corrected stream and lake network is dense and complex with a high level of details.

Land cover

Initially, we explored various sources of data that could be used to define the required land cover map. Two sets of existing data were selected based on their coverage and standardized format. We built an initial land cover map based on the MODIS Canadian land cover map. This classification, dating back to 2005, was performed by the Canadian Remote Sensing Center (Natural Resources Canada) using MODIS satellite images. To our knowledge, this classification is the most recent that entirely covers Canada. It has a 250-m horizontal resolution and includes 39 different land cover classes. From a hydrological modelling point of view, there are too many land cover classes. Thus, we reduced the number of classes to 7 or 9 for the Upper Yukon River watershed. There is no need of having a large number of land cover classes as they will mostly end up having similar or identical parameter values. Table 2.1 presents the regrouped classes of the MODIS classification.

Second, we built a supplementary land cover map based on the Canadian 2000 CIRCA classification from Natural Resources Canada. This classification which covers the whole country was performed with Landsat images. When compared to the MODIS classification, the CIRCA classification has a better horizontal resolution (*i.e.*, 30 m) which incidentally matches the DEM resolution. It includes 43 different land cover classes. Again to ensure a certain agreement with the MODIS classification, we reduced the number of classes to 7 or 9 for the Upper Yukon River watershed. Table 2.2 presents the regrouped classes for the CIRCA classification.

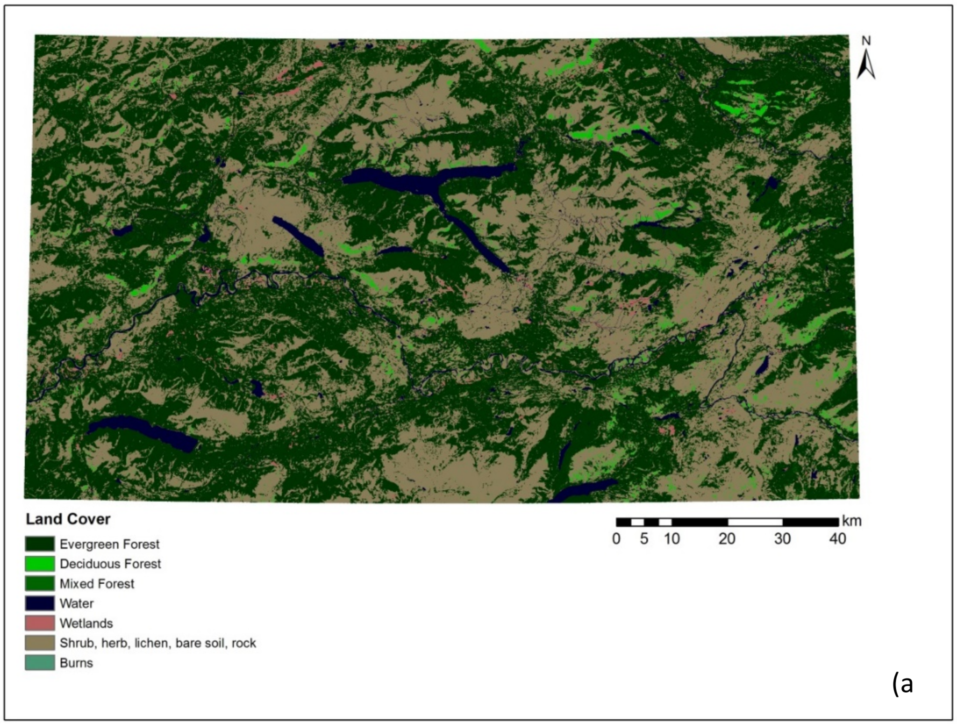
Table 2.2 Regrouped classes of the MODIS classification for the Mayo and Aishihik watersheds

MODIS classes	Regrouped classes
Temperate or subpolar needle-leaved evergreen closed tree canopy (1)	Evergreen Forest
Cold deciduous closed tree canopy (2)	Deciduous Forest
Mixed needle-leaved evergreen – cold deciduous closed tree canopy (3)	Mixed Forest
Mixed needle-leaved evergreen – cold deciduous closed young tree canopy (4)	Mixed Forest
Mixed cold deciduous – needle-leaved evergreen closed tree canopy (5)	Mixed Forest
Temperate or subpolar needle-leaved evergreen medium density, moss-shrub understory (6)	Evergreen Forest
Temperate or subpolar needle-leaved evergreen medium density, lichen-shrub understory (7)	Evergreen Forest
Temperate or subpolar needle-leaved evergreen low density, shrub-moss understory (8)	Evergreen Forest
Temperate or subpolar needle-leaved evergreen low density, lichen (rock) understory (9)	Evergreen Forest
Temperate or subpolar needle-leaved evergreen low density, poorly drained (10)	Evergreen Forest
Cold deciduous broad-leaved, low to medium density (11)	Deciduous Forest
Cold deciduous broad-leaved, medium density, young regenerating (12)	Deciduous Forest
Mixed needle-leaved evergreen – cold deciduous, low to medium density (13)	Mixed Forest
Mixed cold deciduous - needle-leaved evergreen, low to medium density (14)	Mixed Forest
Low regenerating young mixed cover (15)	Mixed Forest
High-low shrub dominated (16)	Shrub, Herb, lichen, bare soil, rock
Herb-shrub-bare cover (18)	Shrub, Herb, lichen, bare soil, rock
Wetlands (19)	Wetlands
Sparse needle-leaved evergreen, herb-shrub cover (20)	Shrub, Herb, lichen, bare soil, rock
Polar grassland, herb-shrub (21)	Shrub, Herb, lichen, bare soil, rock
Shrub-herb-lichen-bare (22)	Shrub, Herb, lichen, bare soil, rock
Herb-shrub poorly drained (23)	Shrub, Herb, lichen, bare soil, rock
Lichen-shrub-herb-bare soil (24)	Shrub, Herb, lichen, bare soil, rock
Low vegetation cover (25)	Shrub, Herb, lichen, bare soil, rock
High biomass cropland (27)	Shrub, Herb, lichen, bare soil, rock
Lichen barren (30)	Shrub, Herb, lichen, bare soil, rock
Lichen-spruce bog (32)	Wetlands
Rock outcrops (33)	Shrub, Herb, lichen, bare soil, rock
Recent burns (34)	Burns
Old burns (35)	Burns
Urban and Built-up (36)	Urban
Water bodies (37)	Water
Mixes of water and land (38)	Water
Snow / Ice (39)	Water / Snow/Ice (uYRW)

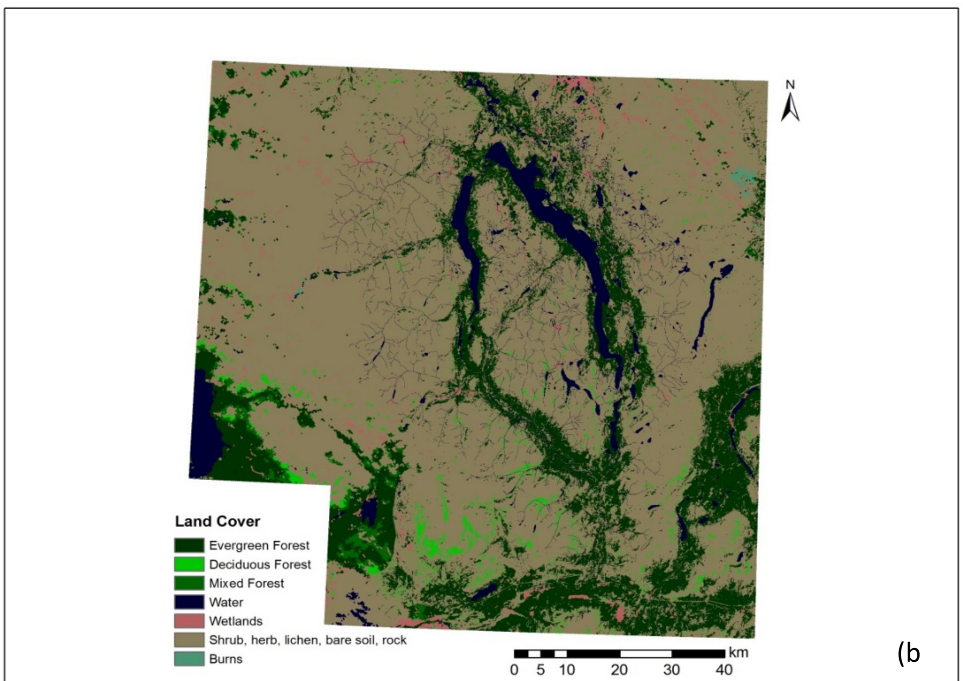
Table 2.3 Regrouped classes of the CIRCA classification for the Mayo and Aishihik Watersheds

CIRCA classes	Regrouped
Cloud(11)	No Data
Shadow (12)	No Data
Water (20)	Water
Snow/Ice (31)	Water / Snow/Ice (uYRW)
Rock/Rubble (32)	Shrub, Herb, lichen, bare soil, rock
Exposed land (33)	Shrub, Herb, lichen, bare soil, rock
Bryoids (40)	Shrub, Herb, lichen, bare soil, rock
Shrub tall (51)	Shrub, Herb, lichen, bare soil, rock
Shrub low (52)	Shrub, Herb, lichen, bare soil, rock
Wetland - Treed (81)	Wetlands
Wetland - Shrub (82)	Wetlands
Wetland - Herb (83)	Wetlands
Herb (100)	Shrub, Herb, lichen, bare soil, rock
Coniferous Dense (211)	Evergreen Forest
Coniferous Open (212)	Evergreen Forest
Coniferous Sparse (213)	Evergreen Forest
Broadleaf Dense (221)	Deciduous Forest
Broadleaf Open (222)	Deciduous Forest
Mixedwood Open (232)	Mixed Forest
Mixedwood Sparse (233)	Mixed Forest

Regarding the two available products, we decided to use the land cover map build from the CIRCA classification since the 30-m resolution of the latter corresponded to that of the DEMs. Furthermore, for both watersheds, the No Data of the CICRA classification were corrected using the more recent MODIS classification (2005 versus 2000). This correction affected more the Aishihik Watershed because of a larger non-classified area on the CIRCA classification. Figure 2.2 shows the resulting land cover maps of the Mayo, Aishihik and Upper Yukon Watersheds. Also, for all watersheds, the stream and lake networks were superimposed on the original classification in order to properly match the water routing and the land cover. Note also that the Alaska National Land Cover Database classification was included to have a complete coverage of the Upper Yukon River watershed. Moreover, this latter watershed included two additional classes, namely Urban and Snow/Ice due to the presence of denser urban areas and glaciers in the upstream portion of the watershed.


N
Land Cover
Evergreen Forest
Deciduous Forest
Mixed Forest
Water
Wetlands
Shrub, herb, lichen, bare soil, rock
Burns
km
0 5 10 20 30 40

(a


N
Land Cover
Evergreen Forest
Deciduous Forest
Mixed Forest
Water
Wetlands
Shrub, herb, lichen, bare soil, rock
Burns
km
0 5 10 20 30 40

(b
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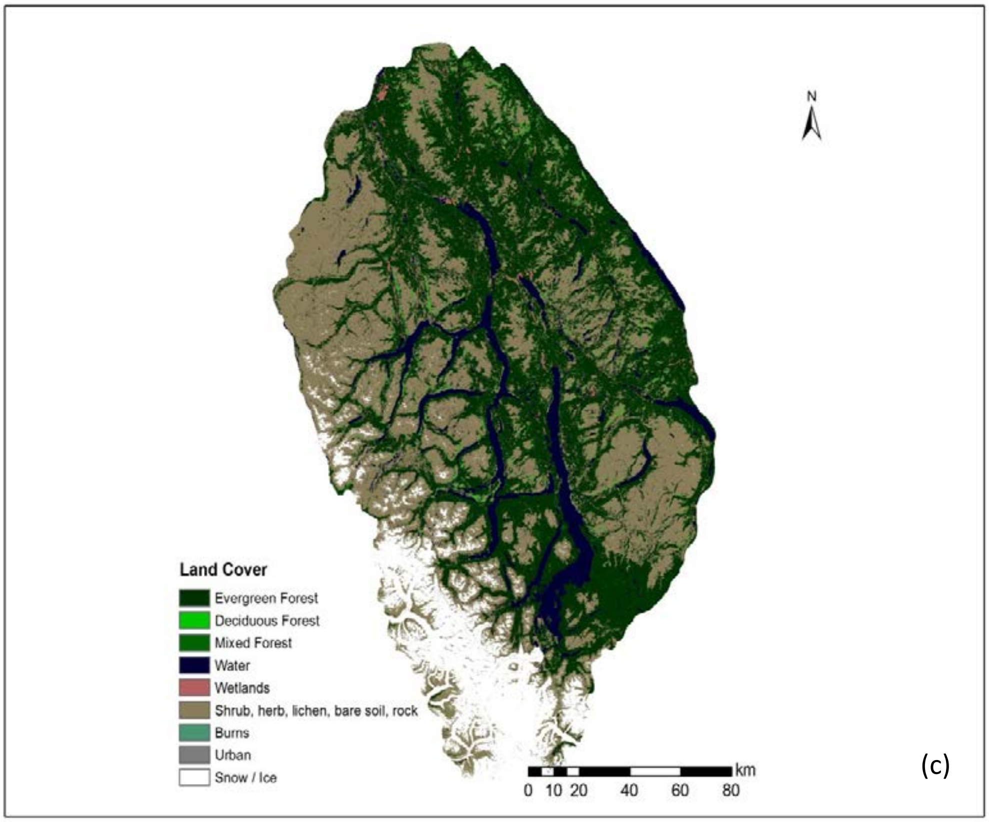


Figure 2.2 Land cover maps: (a) Mayo, (b) Aishihik and (c) Upper Yukon River Watersheds.

It can be mentioned the Geomatics Yukon website offers other land cover products that focus mainly on forest resources. Namely, Vegetation and Vegetation Inventory products were not used to produce the land cover maps because they solely depict the presence or absence of forested areas and give information on tree species for the forest industry. From a hydrological modelling perspective, there is no need for a complete coverage of the area and the type of trees does not need to be as precise as that reported in the Vegetation Inventory. Indeed, ultimately the land cover classes will be regrouped in integrated classes with specific parameter values. Should there be a need to use such products, we could take the time to attempt to improve the land cover map, but without any guaranty of improving the hydrological modelling.

Soil type

The Geomatics Yukon website currently offers limited information on soil texture. Bedrocks geology does not provide the needed information and the associated data only cover limited areas of the Mayo and Upper Yukon River Watershed; while there is no soil information for the Aishihik Watershed. That is why we have decided to look for other sources of information. Based on previous work performed in northern Quebec, there exists an alternative soil texture map covering Northern America at a 1-km resolution.

From a hydrological modelling perspective, HYDROTEL conceptualizes the soil profile as a series of different soil layers with constant hydrodynamics properties. When field measurements are unavailable, default values based on the work of Rawls and Brakensiek (1989) can be used, given basic soil texture information, namely percentages of sand, silt and clay.

The soil type maps developed for the Mayo, Aishihik and Upper Yukon River Watersheds are based on percentages of sand and clay available for three soil layers. These maps were derived from the work of Szeto *et al*. (2008) and they are based on the Soil Landscape of Canada V.2.2. It is the same data that were used as input data to the Canadian Land Surface Scheme (CLASS) of the Canadian Regional Climate Model. It is noteworthy that these maps do not provide any information on non-mineral land cover such as water, outcrops, and organic soils, as they cannot be related to any soil texture composition. The soil type maps were derived as follows.

1. For each 1-km tile and soil horizon (0-10cm; 10-25cm; 25-375cm), the soil type was defined by percentages of sand, clay and silt based on the following soil texture triangle (Figure 2.3).

2. Development of a soil type map for the second soil layer (10-25cm). HYDROTEL allows for the use of a different soil type map for each soil layer required by the vertical water budget sub-model (BV3C). Given the coarse spatial resolution of the basic information, it was decided to use a unique soil type map valid for all three soil layers based on the information available for the second soil layer of the reference data. However, in the presence of a non-mineral soil type, the information available for layer one or layer three were used to substitute the non-mineral soil with the mineral soil information when available. Nonetheless, the resulting maps for all watersheds include non-mineral soils with default values for hydrodynamic properties.

3. The ensuing tiles of 1-km resolution were subdivided into 30-m tiles; that is the resolution of the DEMs.

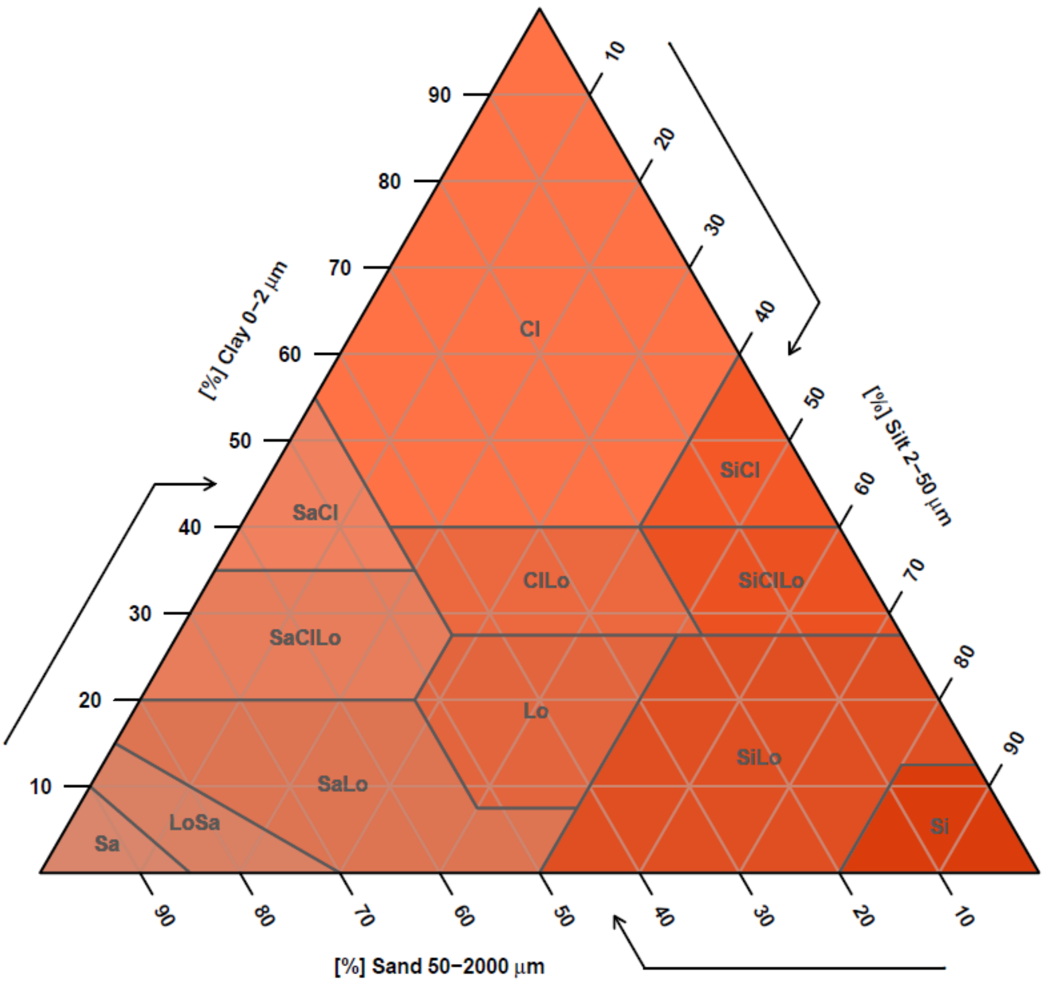
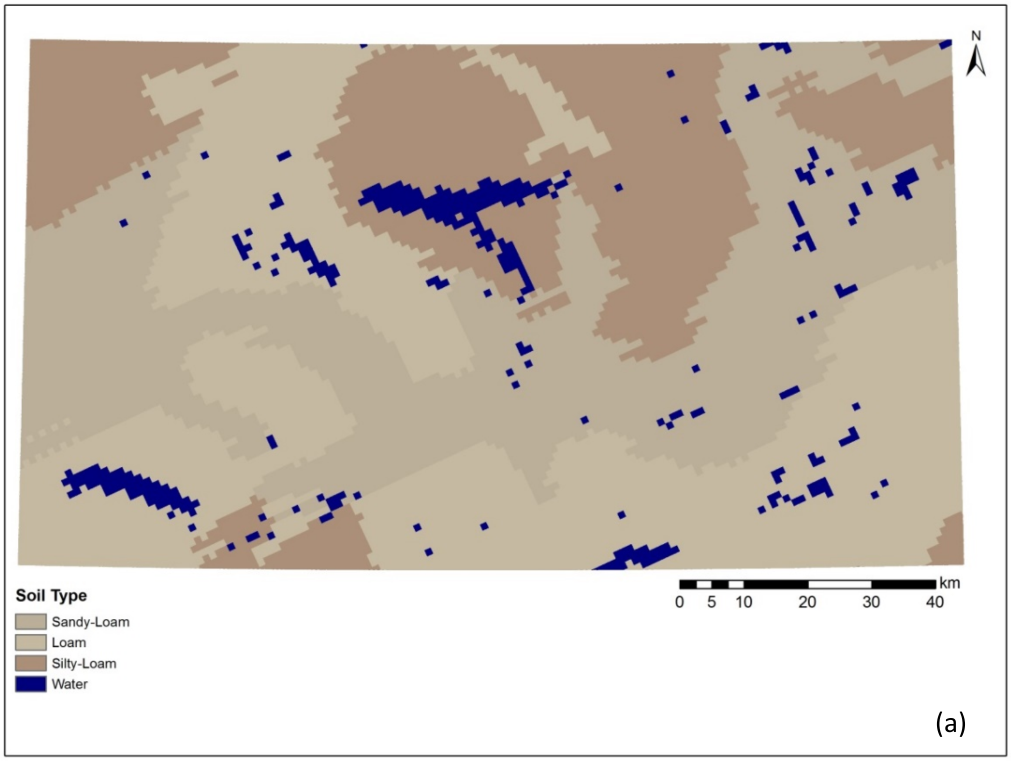
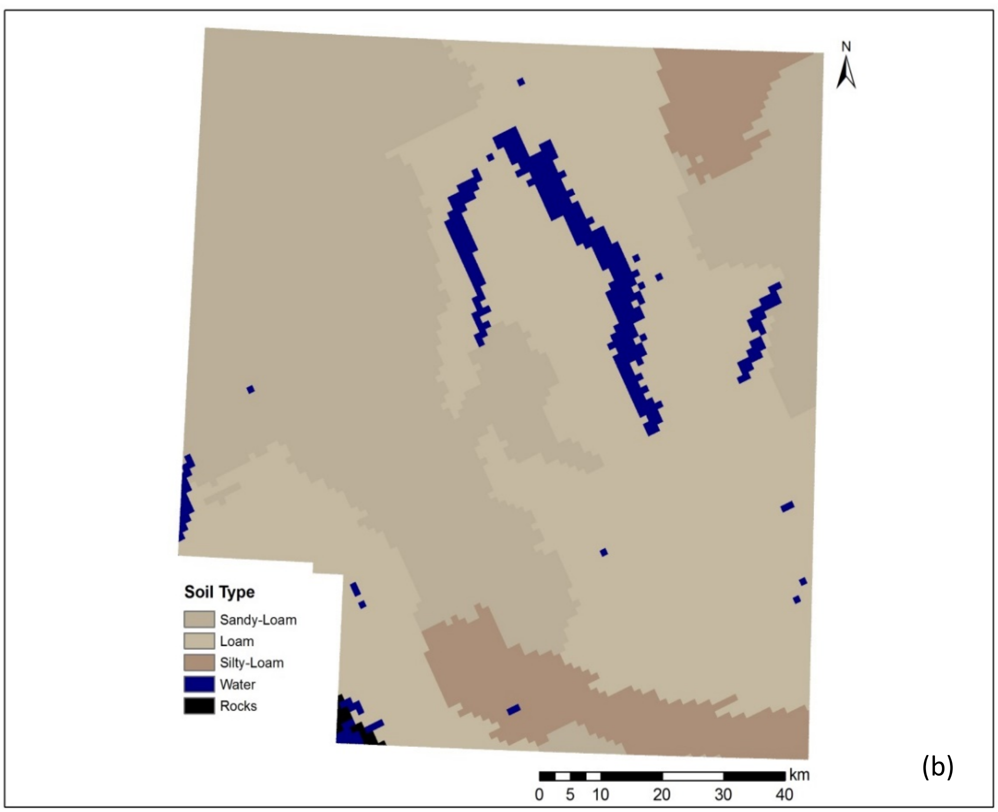


Figure 2.3 Soil texture triangle (Moeys, 2009).

Abbreviations used within the triangle are: Cl : clay, SiCl : silty-clay, SaCl : sandy-clay, SiClLo : silty-clay-loam, ClLo : clay-loam, SaClLo : sandy-clay-loam, SiLo : silty-loam, Lo : loam, SaLo : sandy-loam, Si : silt, LoSa : loamy-sand, Sa : sand.

Figure 2.4 introduces the resulting soil type maps for the Mayo, Aishihik and Upper Yukon River Watersheds.


N
km
0 5 10 20 30 40
Soil Type
Sandy-Loam
Loam
Silty-Loam
Water
(a)


N
Soil Type
Sandy-Loam
Loam
Silty-Loam
Water
Rocks
km
0 5 10 20 30 40
(b)

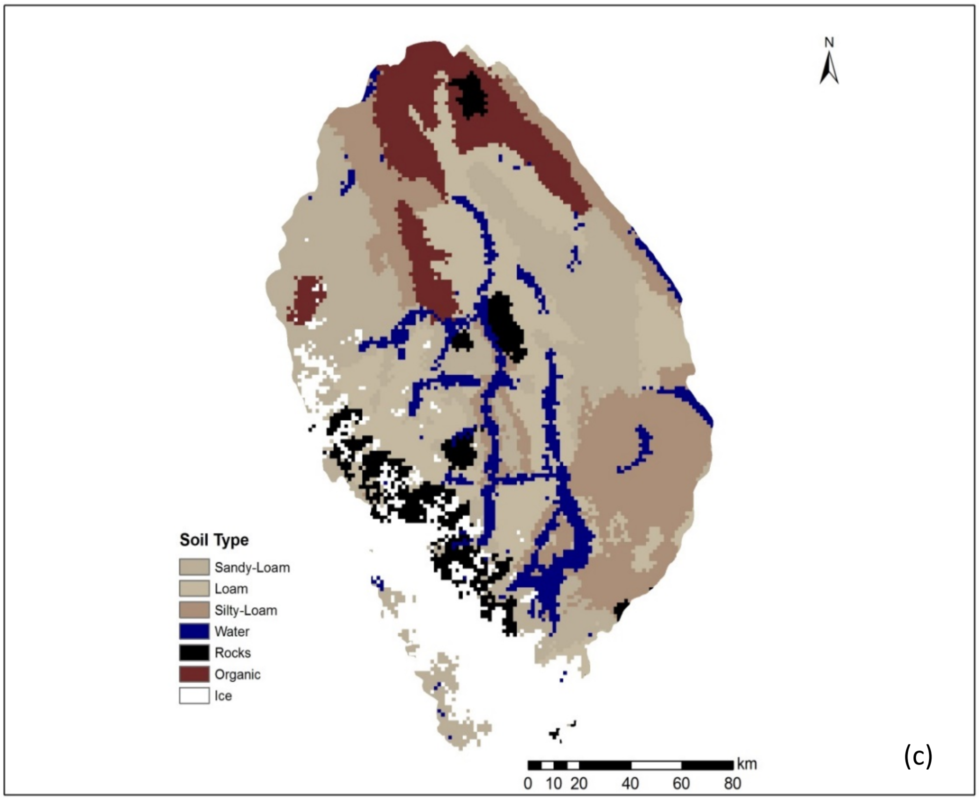


Figure 2.4 Soil type maps: of (a) Mayo, (b) Aishihik) and (c) Upper Yukon River Watersheds.

As mentioned earlier, there exists in PHYSITEL a table relating the soil textures of various soil types developed by Rawls and Brakensiek (1989). It is noteworthy that non-mineral textures can be added to the existing table. Using the soil type map, PHYSITEL determines the dominant soil type of each RHHU. Using the hydrodynamic soil properties look-up table, HYDROTEL estimates the ensuing properties for each RHHU. For mineral soils, the hydrodynamic properties correspond to the default values described in the Rawls and Brakensiek (1989). For non-mineral soils, the hydrodynamic properties have to be determined. Similarly to the works of Jutras et *al*. (2009), these properties for clay were assigned to the water, rocks, ice and outcrop classes. Then again, if required the user can further modify all hydrodynamic properties by simply editing the *proprietehydrolique.sol* file.

2.2.2. Watershed discretization using PHYSITEL

Using a DEM, a soil type map, a land cover map, and optionally a hydrographic network; PHYSITEL computes physiographic parameters for each RHHU. Namely, PHYSITEL determines the internal drainage structure (slopes and flow directions), watershed boundaries, sub-basin and hillslope boundaries, and hydrographic network. For each RHHU, PHYSITEL calculates the topographic index distribution and characterizes the dominant soil type, and percentages of different land covers. Because of standard data formats and universal data types, output data can be used for a wide range of distributed hydrological models. What differentiates PHYSITEL from most GISs are the following characteristics: (i) use of the D8-LTD algorithm of Orlandini et *al*. (2003) to compute the flow matrix, (iii) access to editing tools to modify the flow matrix and correct the stream and lake network, and (iii) optional use of a hydrographic network to determine the internal drainage structure of a watershed.

PHYSITEL can be described as a step by step wizard that guides and helps the user to proceed to watershed discretization. Figure 2.5 summarizes the PHYSITEL input data and data processing.

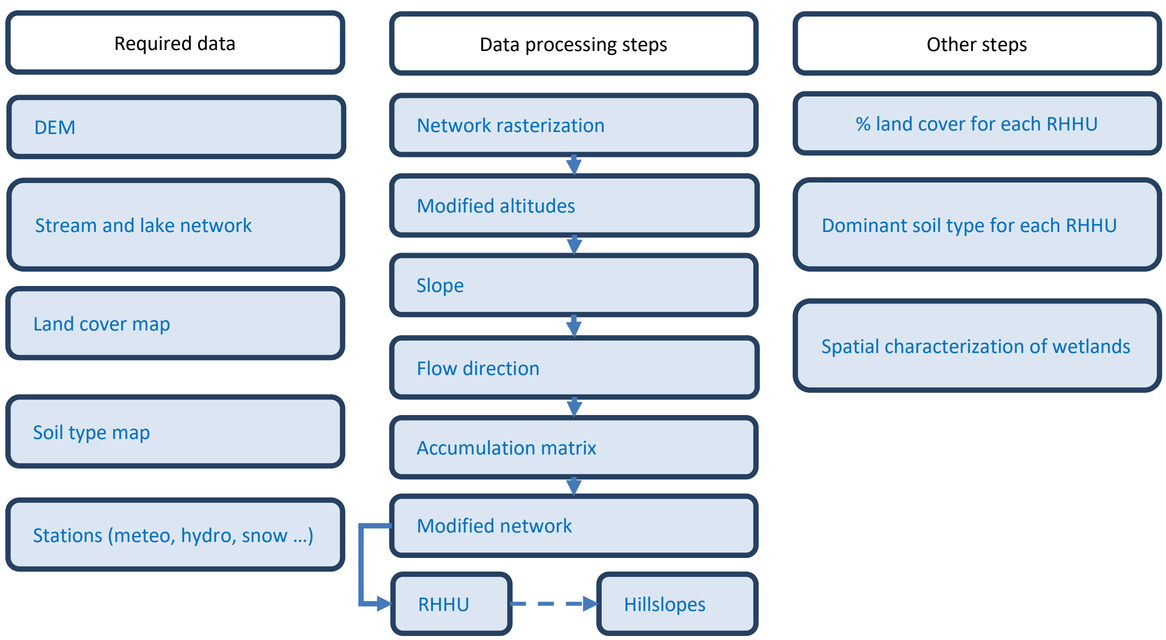


Figure 2.5 PHYSITEL – Input data and data processing.

The different steps of data processing can be described as follows:

1. After correcting the stream and lake network, the vector and polygon network is converted into a raster file.

2. The rasterized network is burned on the DEM to facilitate water routing to and through the network.

3. Using the DEM, PHYSITEL calculates the slope of each cell or tile based on the north-south and east-west transects of each cell.

4. Again for each cell composing the DEM, PHYSITEL calculates the flow direction matrix using the D8-LTD algorithm of Orlandini et *al*. (2003).

5. Based on the flow direction of each cell, PHYSITEL determines the flow accumulation matrix that is for each cell the number of upstream drained cell. For a given outlet, such matrix regroups all the drained upstream cells.

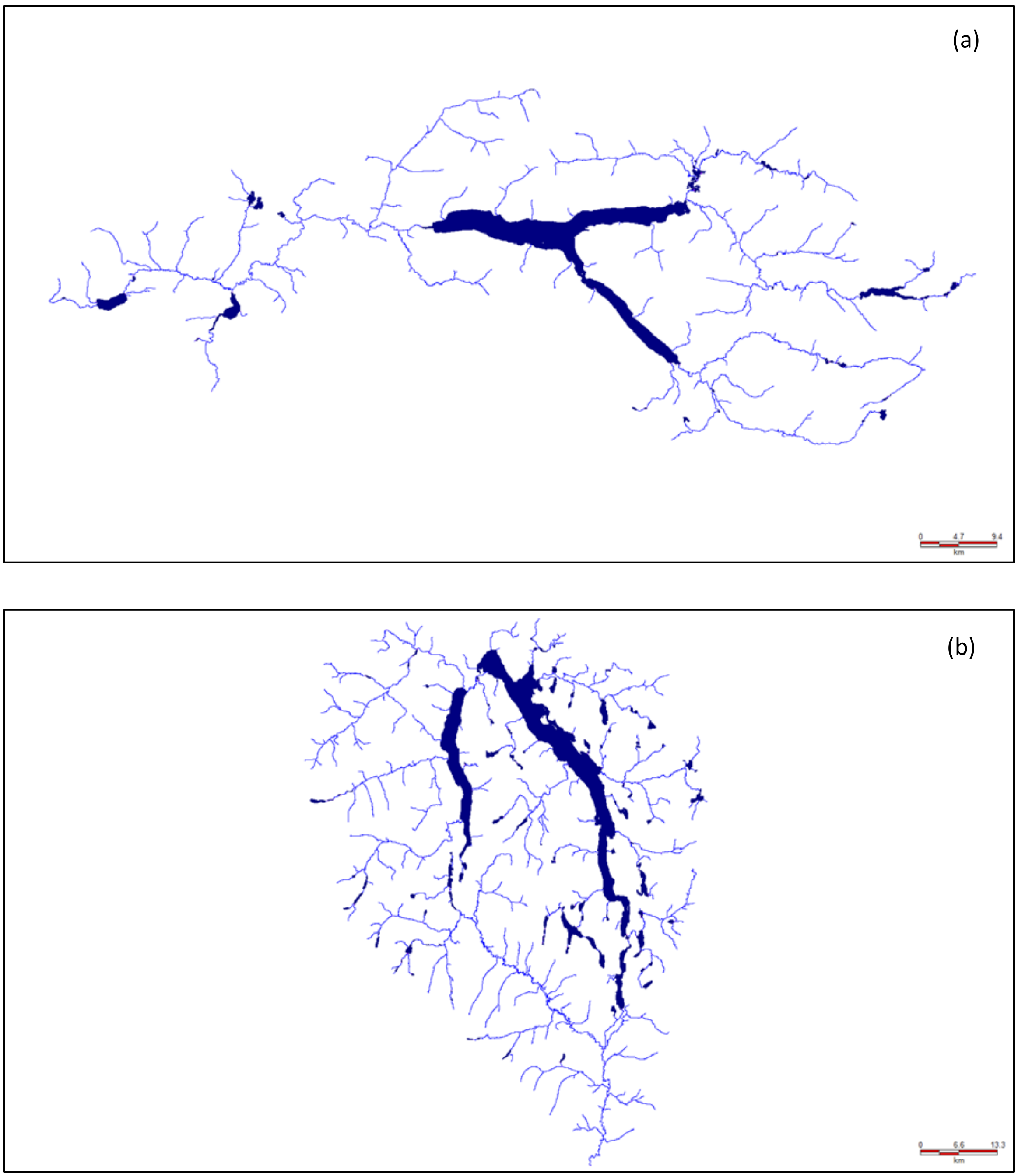
6. Depending on the complexity of the streams and lakes, PHYSITEL allows for the derivation of the hydrologic network using either one of the following options. First, the final network can be identical to the imported and rasterized network. Second, the user can specify a threshold that determines the inclusion or not of a cell into the final network based on the number of upstream drained cells.

7. PHYSITEL identifies the drained cells of each stream or lake to determine the RHHUs. PHYSITEL subdivides the RHHUs into hillslopes in order to have a better representation of the terrain mean slope and mean aspect.

8. Following the RHHU or hillslope delineation, PHYSITEL calculates the land cover percentages and dominant soil type of each RHHU.

For Mayo and Aishihik, a threshold of 5000 upstream drained cells was used; while a 30000 upstream drained cells was set for the Upper Yukon River Watershed to produce a simplified hydrological network for the hydrological forecasting system. This way, a reduced number of streams and lakes will be supported by a more reasonable number of RHHUs.

Figures 2.6 and 2.7 present the final hydrographic networks and hillslope subdivisions for the Mayo, Aishihik and Upper Yukon River Watersheds.



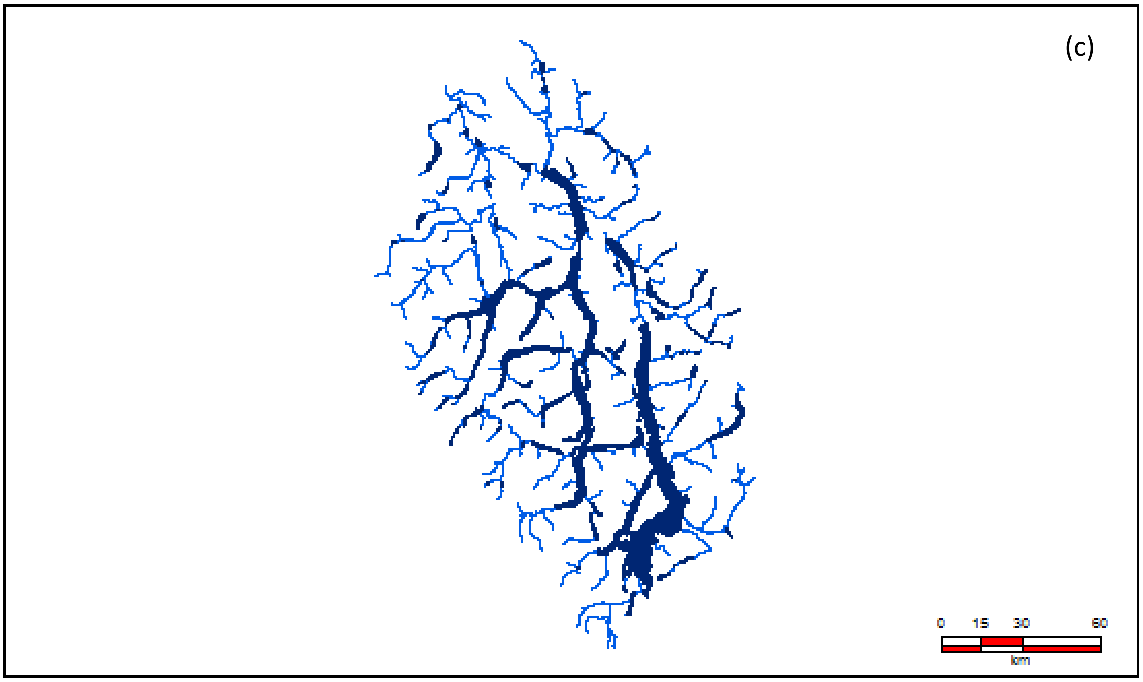
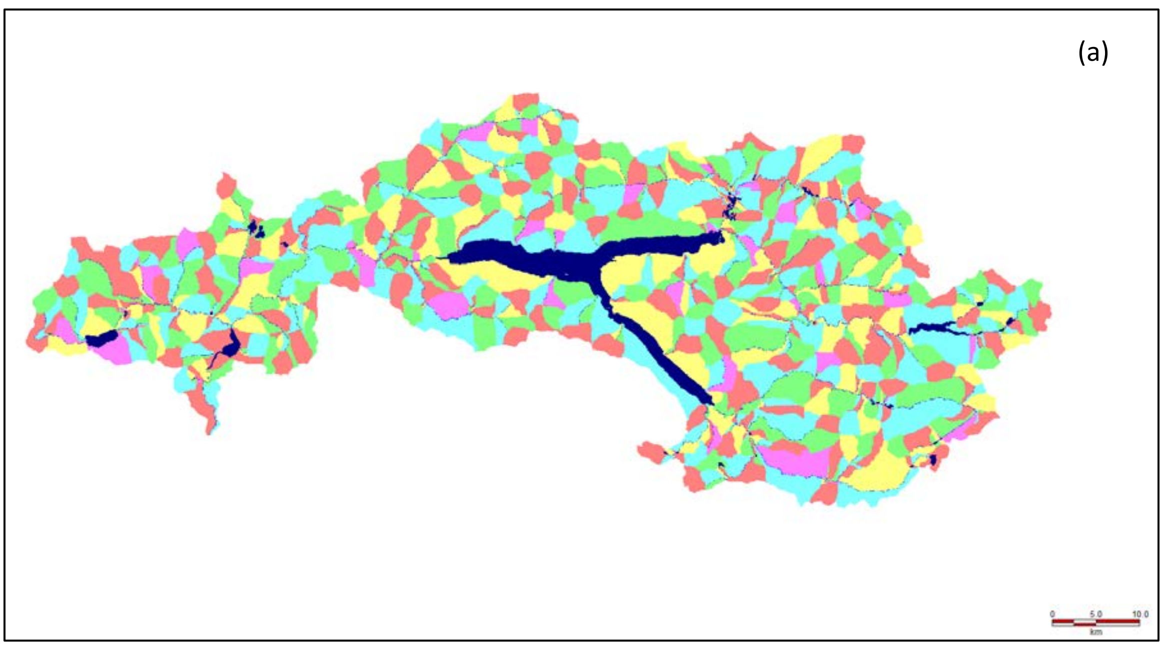
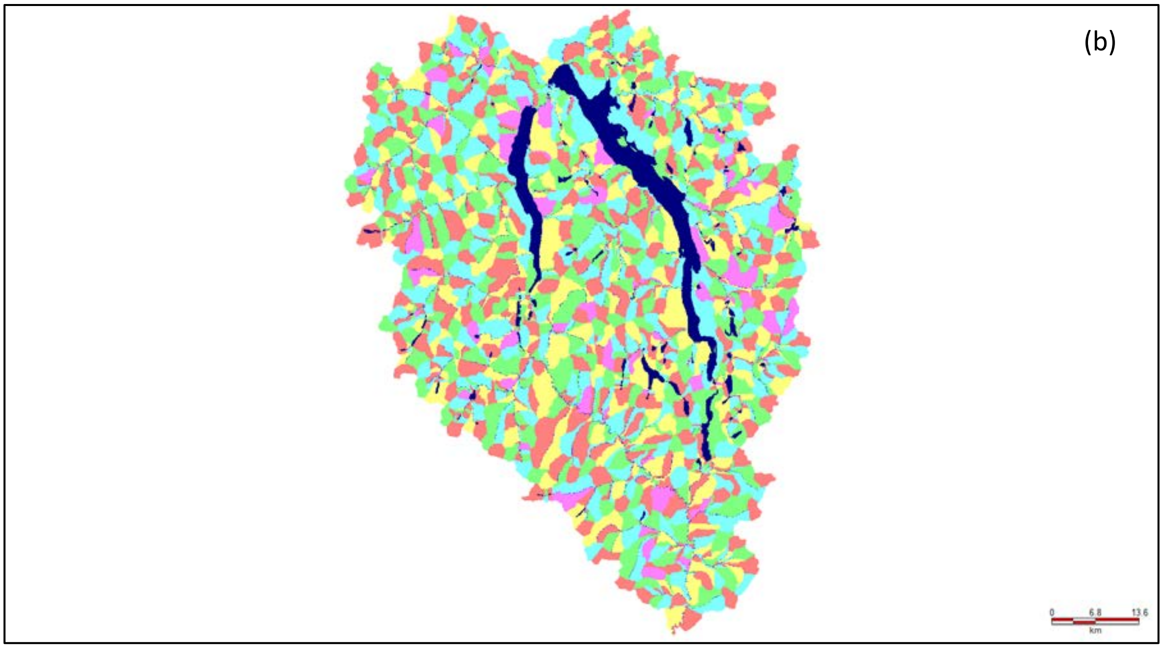


Figure 2.6 Modelled hydrological networks for: (a) Mayo, (b) Aishihik and (c) Upper Yukon River Watersheds.





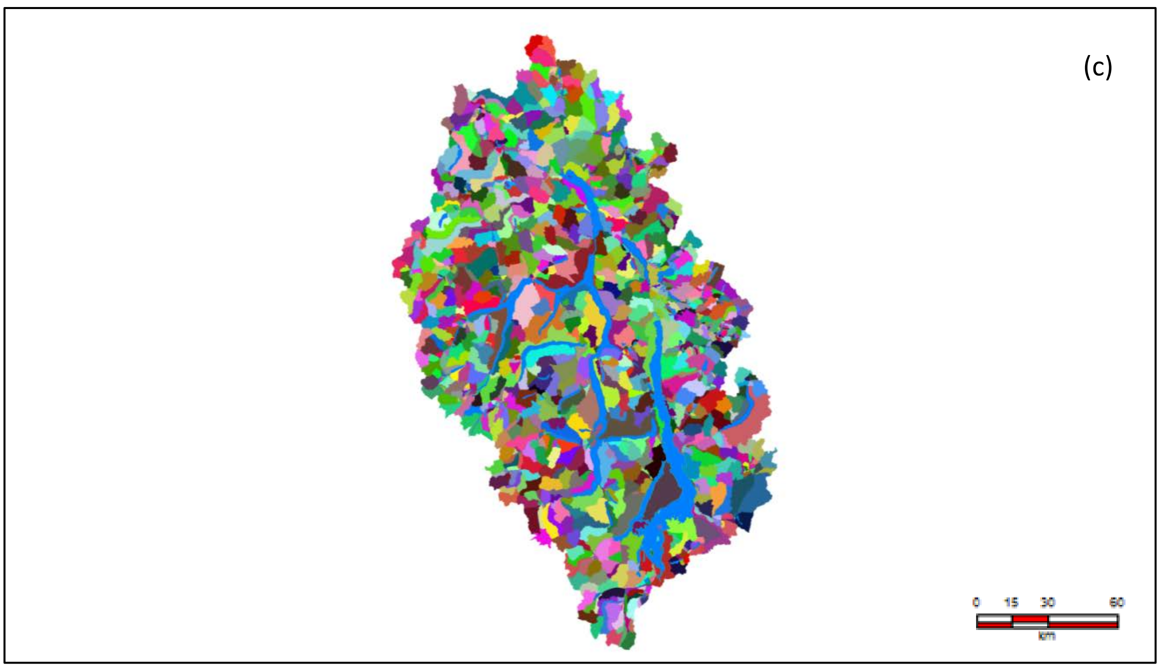


Figure 2.7 RHHU / Hillslope delineation of Mayo (a) Aishihik (b) and (c) Upper Yukon River Watersheds.

The distinctive color pattern for the Upper Yukon River Watershed relates to the use of a newer version of PHYSITEL to perform watershed discretization. This newer version allows for larger watershed to be discretized.

Table 2.4 summarizes the modelling characteristics of the discretized Mayo, Aishihik and Upper Yukon River Watersheds.

Table 2.4 Modelling characteristics of the discretized Mayo, Aishihik and Upper Yukon River Watersheds.

	Mayo	Aishihik	Upper Yukon River
Number of RHHUs as Hillslope	838	1737	1960
Mean RHHU area	3.19km²	2.63km²	10.39km²
Number of stream and lakes	311	668	702

The RHHU mean area for the Upper Yukon is larger than those for Mayo and Aishihik. The reason is simply related to the number of RRHUs that are used to represent a larger watershed. The number of RHHUs remains under 2000 in order to have an acceptable computational time for simulation and data assimilation for each watershed. It is noteworthy that the data assimilation scheme developed by NCE limits the maximum number of RHHUs to 2000.

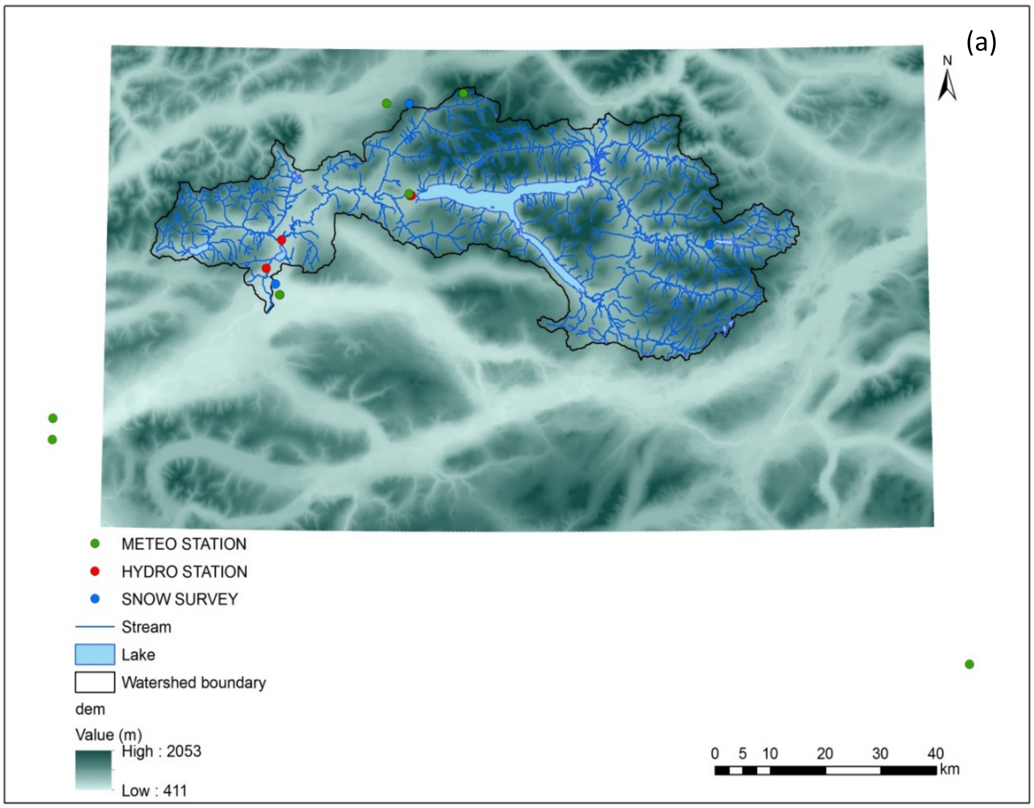
The final step corresponds to the identification of nearby meteorological stations own by Environment and Climate Change Canada and to the downloading of historical and available data (temperature and precipitations).

2.2.3. HYDROTEL integration and hydrological simulation

Integration of the Mayo, Aishihik and Upper Yukon River Watersheds to HYDROTEL is supported by the different files created by PHYSITEL; while simulations are driven by hydrometeorological data. Model calibration requires observed stream flows or reconstructed reservoir/lake inflows and any other relevant state variables (*e.g.*, SWE). From a hydrological modelling perspective, HYDROTEL is a semi-distributed model; that is based on one-dimensional and two dimensional governing equations. Given the available meteorological data for the studied watersheds, the model runs on a daily time step. The computational domain is made of interconnected river segments (RSs) and three-soil-layer hillslopes, referred to as relatively homogeneous hydrological units (RHHUs) as depicted previously.

Prior to any model simulations, there a need to build a satisfying hydrometeorological database with continuous meteorological data and relevant streamflow or reconstructed reservoir/lake inflows. Such data, especially available stream flows or reservoir/lake inflows should can either be provided by YEC or downloaded from the Water Survey Canada website. Any additional meteorological data located within or near the studied watersheds would be welcome and increase the quality of the hydrological simulations. This database also includes snow survey measurements (snow height and SWE) that can be assimilated during the production of the hydrological forecasts.

Figure 2.8 and Table 2.5 present the different hydrometeorological stations and snow survey sites for all three watersheds.



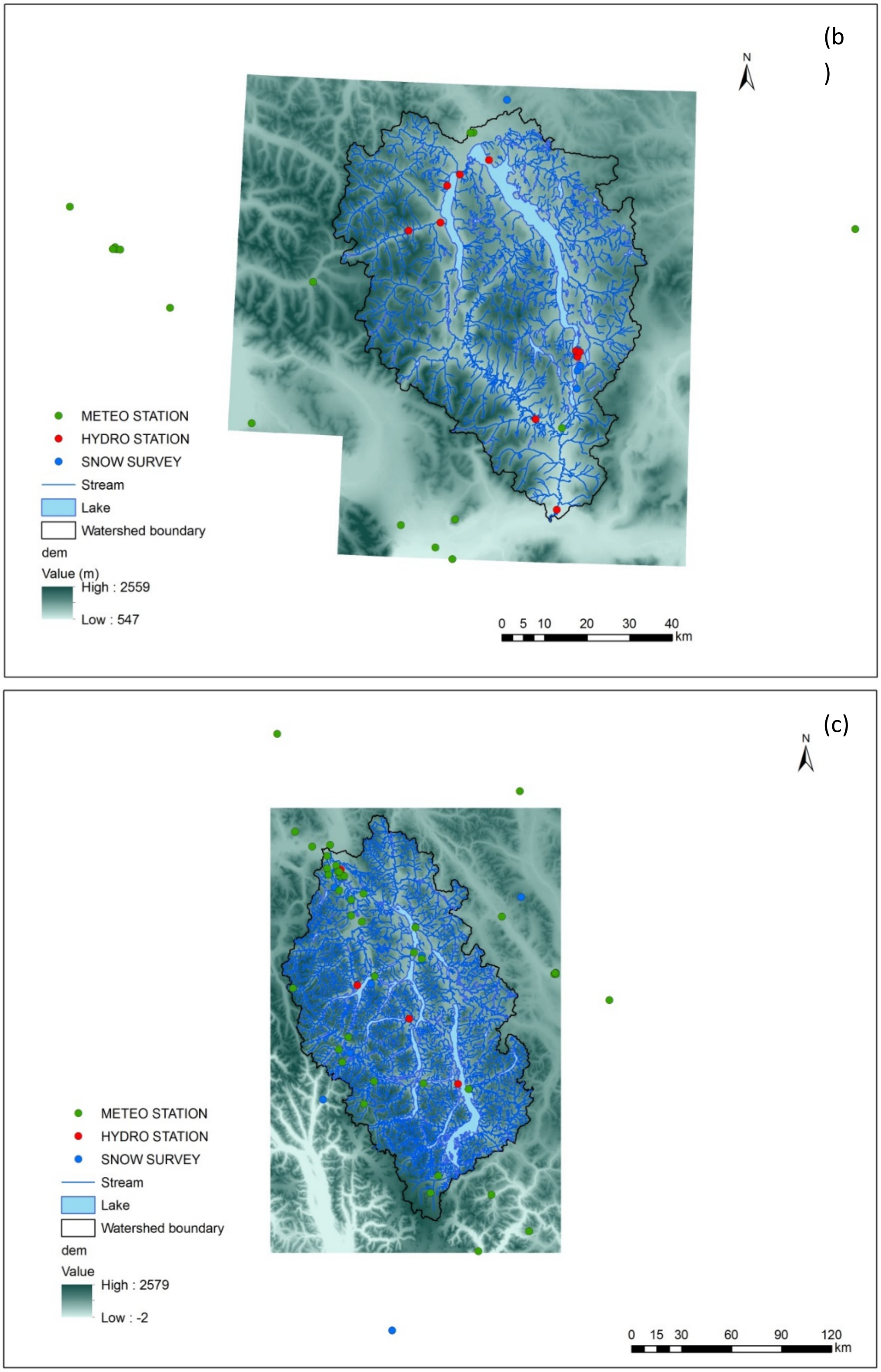


Figure 2.8 Meteorological and hydrometric stations and snow survey sites for Mayo (a) Aishihik (b) and (c) Upper Yukon River Watersheds.

Table 2.5 Meteorological stations of the Mayo, Aishihik and Upper Yukon River Watersheds.

Mayo

NAME OF THE STATION	PROVINCE	STATION #	DATA	START	END	TIME STEP	TYPE	DATA FROM
DRURY CREEK	YT	2100460	T. AND P.	1970	2009	DAILY	MANUAL	MSC
ELSA	YT	2100500	T. AND P.	1948	1989	DAILY	MANUAL	MSC
KENO HILL	YT	2100677	T. AND P.	1974	1982	DAILY	MANUAL	MSC
MAYO A	YT	2100700	T. AND P.	1924	2013	HOURLY AND DAILY	AUTO. AND MANUAL	MSC
MAYO A	YT	2100701	T. AND P.	2013	2017	HOURLY AND DAILY	AUTO. AND MANUAL	MSC
MOOSE CREEK	YT	2100746	T. AND P.	1972	1975	DAILY	MANUAL	MSC
RUSSELL CREEK	YT	2100942	T. AND P.	1989	1993	DAILY	MANUAL	MSC
STEWART CROSSING	YT	2101030	T. AND P.	1953	2008	DAILY	MANUAL	MSC
STEWART CROSSING TOWER	YT	2101031	T. AND P.	1976	1976	DAILY	MANUAL	MSC
TWO PETE CREEK	YT	2101138	T. AND P.	1979	1984	DAILY	MANUAL	MSC
MAYOMET	YT	MAYOMET	T. AND P.	2017	2017	HOURLY AND DAILY	AUTO. AND MANUAL	YEC-YNC

Aishihik

NAME OF THE STATION	PROVINCE	STATION #	DATA	START	END	TIME STEP	TYPE	DATA FROM
MULE CREEK	BC	1205248	T. AND P.	1970	1986	DAILY	MANUAL	MSC
WINDY CRAGGY	BC	120HRNP	T. AND P.	1987	1990	DAILY	MANUAL	MSC
AISHIHIK A	YT	2100100	T. AND P.	1943	1966	HOURLY AND DAILY	MANUAL	MSC
BLANCHARD RIVER	YT	2100163	T. AND P.	1986	2012	DAILY	AUTOMATIC	MSC
BRAEBURN	YT	2100167	T. AND P.	1974	1995	DAILY	MANUAL	MSC
BURWASH	YT	2100179	T. AND P.	1993	2004	HOURLY AND DAILY	AUTOMATIC	MSC
BURWASH A	YT	2100181	T. AND P.	2011	2017	HOURLY AND DAILY	AUTO. AND MANUAL	MSC
BURWASH A	YT	2100182	T. AND P.	1966	2015	HOURLY AND DAILY	AUTOMATIC	MSC
BURWASH AIRPORT AUTO BC	YT	2100184	T. AND P.	2013	2017	HOURLY AND DAILY	AUTOMATIC	MSC
CARMACKS	YT	2100300	T. AND P.	1963	2008	DAILY	MANUAL	MSC
CARMACKS CS	YT	2100301	T. AND P.	1999	2017	HOURLY AND DAILY	AUTOMATIC	MSC
CARMACKS TOWER	YT	2100302	T. AND P.	1974	1976	DAILY	MANUAL	MSC
DESTRUCTION BAY	YT	2100418	T. AND P.	1975	1984	DAILY	MANUAL	MSC
DEZADEASH	YT	2100430	T. AND P.	1974	1986	DAILY	MANUAL	MSC
HAINES APPS #4	YT	2100627	T. AND P.	1969	1971	DAILY	MANUAL	MSC
HAINES JUNCTION	YT	2100630	T. AND P.	1944	2017	HOURLY AND DAILY	AUTOMATIC	MSC
HAINES JUNCTION YTG	YT	2100631	T. AND P.	1985	2008	DAILY	MANUAL	MSC
KLUANE LAKE	YT	2100680	T. AND P.	1946	1983	DAILY	MANUAL	MSC
MINTO	YT	2100744	T. AND P.	1974	1974	DAILY	MANUAL	MSC
OTTER FALLS NCPC	YT	2100840	T. AND P.	1980	2015	DAILY	MANUAL	MSC
PAINT MOUNTAIN TOWER	YT	2100850	T. AND P.	1976	1976	DAILY	MANUAL	MSC
PELLY RANCH	YT	2100880	T. AND P.	1898	2015	DAILY	MANUAL	MSC
QUILL CREEK	YT	2100914	T. AND P.	1983	1985	DAILY	MANUAL	MSC

MIDWAY LODGE	YT	2100PLF	T. AND P.	1987	1988	DAILY	MANUAL	MSC
TAKHINI RIVER RANCH	YT	2101095	T. AND P.	1980	2015	DAILY	MANUAL	MSC
GLADSTONE MET STATION	YT	GLADMET	T. AND P.	2009	2012	HOURLY	AUTOMATIC	YEC
AISHIHIK MET STATION	YT	AISHMET	T. AND P.	2017	2017		AUTOMATIC	YEC-YNC

Upper Yukon River

NAME OF THE STATION	PROVINCE	STATION #	DATA	START	END	TIME STEP	TYPE	DATA FROM
ATLIN	BC	1200560	T. AND P.	1899	2017	DAILY	MANUAL	MSC
BENNET	BC	1200847	T. AND P.	1972	1974	DAILY	MANUAL	MSC
GRAHAM INLET	BC	1203255	T. AND P.	1973	2011	DAILY	MANUAL	MSC
LINDEMAN CITY	BC	1204632	T. AND P.	1968	1981	DAILY	MANUAL	MSC
NAKONAKE RIVER	BC	1205295	T. AND P.	1956	1956	DAILY	MANUAL	MSC
FRASER CAMP	BC	120C036	T. AND P.	1980	2008	DAILY	MANUAL	MSC
ANNIE LAKE ROBINSON	YT	2100115	T. AND P.	1976	2006	DAILY	MANUAL	MSC
BRAEBURN	YT	2100167	T. AND P.	1974	1995	DAILY	MANUAL	MSC
BRYN NYRDDIN FARM	YT	2100174	T. AND P.	1988	1996	DAILY	AUTOMATIC	MSC
CARCROSS	YT	2100200	T. AND P.	1907	2008	DAILY	MANUAL	MSC
FISH LAKE ROAD	YT	2100535	T. AND P.	1988	1989	DAILY	MANUAL	MSC
GOLDEN HORN	YT	2100615	T. AND P.	1989	1994	DAILY	MANUAL	MSC
HAECKEL HILL TOWER	YT	2100620	T. AND P.	1974	1976	DAILY	MANUAL	MSC
JOHNSONS CROSSING	YT	2100670	T. AND P.	1963	1995	DAILY	MANUAL	MSC
MARSH LAKE	YT	2100698	T. AND P.	1994	2002	DAILY	MANUAL	MSC
MAYO ROAD	YT	2100709	T. AND P.	1983	2016	DAILY	MANUAL	MSC
NEW IMPERIAL	YT	2100765	T. AND P.	1968	1969	DAILY	MANUAL	MSC
PORTER CREEK WAHL	YT	2100907	T. AND P.	1989	2005	DAILY	MANUAL	MSC
QUIET LAKE	YT	2100910	T. AND P.	1966	1992	DAILY	MANUAL	MSC
MACPHERSON	YT	2100FRN	T. AND P.	1984	1988	DAILY	MANUAL	MSC
TAGISH	YT	2101089	T. AND P.	1979	1984	DAILY	MANUAL	MSC
TAGISH TOWER	YT	2101093	T. AND P.	1976	1976	DAILY	MANUAL	MSC
TAKHINI RIVER RANCH	YT	2101095	T. AND P.	1980	2015	DAILY	MANUAL	MSC
TESLIN	YT	2101099	T. AND P.	1980	1984	DAILY	MANUAL	MSC
TESLIN A	YT	2101100	T. AND P.	1953	2014	HOURLY AND DAILY	AUTO. AND MANUAL	MSC
TESLIN A	YT	2101101	T. AND P.	2014	2017	HOURLY AND DAILY	MANUAL	MSC
TESLIN (AUT)	YT	2101102	T. AND P.	1994	2017	HOURLY AND DAILY	AUTOMATIC	MSC
WHITEHORSE	YT	2101290	T. AND P.	1900	1960	DAILY	MANUAL	MSC
WHITEHORSE A	YT	2101300	T. AND P.	1953	2012	HOURLY AND DAILY	AUTO. AND MANUAL	MSC
WHITEHORSE A	YT	2101303	T. AND P.	2012	2017	HOURLY AND DAILY	AUTOMATIC	MSC
WHITEHORSE AUTO	YT	2101310	T. AND P.	2009	2017	HOURLY AND DAILY	AUTOMATIC	MSC
WHITEHORSE RIVERDALE	YT	2101400	T. AND P.	1959	2012	DAILY	MANUAL	MSC
WHITEHORSE WSO	YT	2101415	T. AND P.	1996	1998	DAILY	MANUAL	MSC
WOLF CREEK	YT	2101600	T. AND P.	1969	1974	DAILY	MANUAL	MSC

WOLF CREEK	YT	2101601	T. AND P.	1985	1989	DAILY	MANUAL	MSC
PORTERS LANDING	BC	1206258	T. AND P.	1972	1972	DAILY	MANUAL	MSC
TULSEQUAH	BC	1208295	T. AND P.	1964	1966	DAILY	MANUAL	MSC
MORLEY RIVER	YT	2100750	T. AND P.	1984	1989	DAILY	MANUAL	MSC
FANTAIL LOWER	BC	FANTLOW	T. AND P.	2012	2017	HOURLY	AUTOMATIC	YRC-YEC
FANTAIL UPPER	BC	FANTUPP	T. AND P.	2012	2017	HOURLY	AUTOMATIC	YRC-YEC
LLEWELLYN LOWER	BC	LLEWLOW	T. AND P.	2013	2017	HOURLY	AUTOMATIC	YRC-YEC
LLEWELLYN UPPER	BC	LLEWUPP	T. AND P.	2013	2016	HOURLY	AUTOMATIC	YRC-YEC
WHEATON	YT	WHEATON	T. AND P.	2014	2017	HOURLY	AUTOMATIC	YRC-YEC

For the three studied watersheds, all meteorological stations own by Environment Canada or YEC with measurements from the 20th century and located within a 200-km radius are included in Table 2.5. For the forecasting system, only stations with current measurements are relevant. Also new or existing stations not related to Meteorological Service of Canada could be added to the previous list. Note that for the Mayo, Aishihik, and Upper Yukon River Watersheds, there are 2, 5 and 9 operational stations, respectively, including recently added meteorological station in Aishihik and Mayo Watersheds. During the calibration process, only the operational stations were considered since the forecasting system. This consideration prevents the use of removed or closed stations for model calibration, since the forecasting system would not be able to use them anyway. Note that the Upper Fantail station was removed from the Upper Yukon River Watershed and relocated within the boundaries of the Mayo Watershed which only had one operational meteorological station. It is noteworthy that operational stations can be located beyond watershed boundaries, but their monitored conditions may note represent those occurring within the watershed boundaries.

Table 2.6 Hydrometric stations of the Mayo, Aishihik and Upper Yukon River Watersheds.

Mayo

NAME OF THE STATION	PROVINCE	STATION #	DATA	START	END	OPERATION	TYPE	DATA FROM
MAYO LAKE NEAR THE OUTLET	YT	09DC005	WATER LEVEL	1979	2017	CONTINUOUS	5 MINUTES	WSC
MAYO RIVER NEAR MAYO	YT	09DC001	FLOW	1945	1951	DISCONTINUOUS	DAILY	WSC
WAREHAM LAKE AT HEADGATE	YT	09DC004	WATER LEVEL	1979	2000	CONTINUOUS	DAILY	WSC
MAYO LAKE AT THE OUTLET	YT	YECMAYO	FLOW	1979	2017	CONTINUOUS	5 MINUTES	YEC
INFLOW TO MAYO LAKE	*YT*	*0000003*	*FLOW*	*1979*	*2017*	*CONTINUOUS*	*DAILY*	*YEC*

Aishihik

NAME OF THE STATION	PROVINCE	STATION #	DATA	START	END	OPERATION	TYPE	DATA FROM
AISHIHIK RIVER NEAR WHITEHORSE	YT	08AA001	FLOW	1950	1986	Contiuous	DAILY	WSC
AISHIHIK LAKE NEAR WHITEHORSE	YT	08AA005	WATER LEVEL	1972	2017	Contiuous	5 MINUTES	WSC
AISHIHIK RIVER BELOW AISHIHIK LAKE	YT	08AA010	FLOW AND WATER LEVEL	1980	2017	Contiuous	5 MINUTES	WSC
GILTANA CREEK NEAR THE MOUTH	YT	08AA009	FLOW AND WATER LEVEL	1980	2017	Contiuous	5 MINUTES	WSC
SEKULMUN LAKE NEAR WHITEHORSE	YT	08AA007	WATER LEVEL	1980	2017	Contiuous	5 MINUTES	WSC
SEKULMUN RIVER AT OUTLET OF SEKULMUN LAKE	YT	08AA008	FLOW AND WATER LEVEL	1981	2017	Contiuous	5 MINUTES	WSC
WEST AISHIHIK RIVER NEAR THE MOUTH	YT	08AA011	FLOW	1995	2000	Contiuous	DAILY	WSC
AISHIHIK LAKE NEAR AISHIHIK	YT	08AA012	WATER LEVEL	1995	2015	Contiuous	5 MINUTES	WSC
ISAAC CREEK 1	YT	ISAAC01	FLOW	2009	2013	Contiuous	5 MINUTES	YEC
ISAAC CREEK 2	YT	ISAAC02	FLOW	2009	2013	Contiuous	5 MINUTES	YEC
INFLOW TO AISHIHIK LAKE	*YT*	*0000003*	*FLOW*	*1980*	*2017*	*CONTINUOUS*	*DAILY*	*YEC*

Upper Yukon River

NAME OF THE STATION	PROVINCE	STATION #	DATA	START	END	OPERATION	TYPE	DATA FROM
YUKON RIVER AT WHITEHORSE	YT	09AB001	FLOW AND WATER LEVEL	1902	2017	Contiuous	5 MINUTES	WSC
ATLIN RIVER NEAR ATLIN	BC	09AA006	FLOW AND WATER LEVEL	1950	2017	Contiuous	5 MINUTES	WSC
WHEATON RIVER NEAR CARCROSS	YT	09AA012	FLOW AND WATER LEVEL	1955	2017	Contiuous	5 MINUTES	WSC
TUTSHI RIVER AT OUTLET OF TUTSHI LAKE	BC	09AA013	FLOW AND WATER LEVEL	1956	2017	Contiuous	5 MINUTES	WSC

For the three watersheds, all the hydrometric stations that were operational at one time or another times are listed in Table 2.6. It is noteworthy that stations that only monitored water levels cannot be used, since HYDROTEL does not simulate reservoir or lake levels. For the forecasting system, some stations will have no use (i.e., non-operational stations, water level stations). Also for Aishihik, ISAAC CREEK 1 and 2 were not used since they have very limited measurements and are located upstream of the Sekulmun River station.

Table 2.7 Snow survey sites for the Mayo, Aishihik and Upper Yukon River Watersheds.

Mayo

NAME OF THE STATION	PROVINCE	COURSE ID #	DATA	START	END	OPERATION	TYPE	DATA FROM
CALUMET	YT	09DD-SC01	DEPTH / SWE	1975	2017	UP TO 5 days / Year	MANUAL	Environment Yukon
EDWARDS LAKE	YT	09DD-SC02	DEPTH / SWE	1987	2016	UP TO 5 days / Year	MANUAL	Environment Yukon
MAYO AIRPORT A	YT	09DC-SC01A	DEPTH / SWE	1968	2017	UP TO 5 days / Year	MANUAL	Environment Yukon
MAYO AIRPORT B	YT	09DC-SC01B	DEPTH / SWE	1987	2017	UP TO 5 days / Year	MANUAL	Environment Yukon

Aishihik

NAME OF THE STATION	PROVINCE	COURSE ID #	DATA	START	END	OPERATION	TYPE	DATA FROM
AISHIHIK LAKE	YT	08AA-SC03	DEPTH / SWE	1994	2017	UP TO 5 days / Year	MANUAL	Environment Yukon
CANYON LAKE	YT	08AA-SC01	DEPTH / SWE	1975	2017	UP TO 5 days / Year	MANUAL	Environment Yukon
MACINTOSH	YT	09CA-SC02	DEPTH / SWE	1976	2016	UP TO 5 days / Year	MANUAL	Environment Yukon
AISHMET	YT	AISHMET	DEPTH / SWE	2017	2017	UP TO 5 days / Year	AUTOMATIC	Yukon College
AISRS01	YT	AISRS01	DEPTH / SWE	2017	2017	UP TO 5 days / Year	MANUAL	Yukon College
AISRS02	YT	AISRS02	DEPTH / SWE	2017	2017	UP TO 5 days / Year	MANUAL	Yukon College

Upper Yukon River

NAME OF THE STATION	PROVINCE	COURSE ID #	DATA	START	END	OPERATION	TYPE	DATA FROM
WHITEHORSE AIRPORT	YT	09AB-SC2	DEPTH / SWE	2006	2017	UP TO 5 days / Year	MANUAL	Environment Yukon
MT. MCINTYRE (B)	YT	09AB-SC1B	DEPTH / SWE	2006	2017	UP TO 5 days / Year	MANUAL	Environment Yukon
TAGISH	YT	09AA-SC1	DEPTH / SWE	2006	2017	UP TO 5 days / Year	MANUAL	Environment Yukon
MONTANA MOUNTAIN	YT	09AA-SC2	DEPTH / SWE	2006	2017	UP TO 5 days / Year	MANUAL	Environment Yukon
LOG CABIN (B.C.)	BC	09AA-SC3	DEPTH / SWE	2006	2017	UP TO 5 days / Year	MANUAL	Environment Yukon

MOORE CREEK BRIDGE	AL	0034K02	DEPTH / SWE	2006	2017	UP TO 5 days / Year	MANUAL	USDA NRCS
ATLIN (B.C.)	BC	09AA-SC4	DEPTH / SWE	2006	2017	UP TO 5 days / Year	MANUAL	Environment Yukon
EAGLECREST	AL	0034J03	DEPTH / SWE	2006	2017	UP TO 5 days / Year	MANUAL	USDA NRCS
MEADOW CREEK	YT	09AD-SC1	DEPTH / SWE	2006	2017	UP TO 5 days / Year	MANUAL	Energy Mines and Ressources Yukon
FANTAIL LOWER	BC	FANTLOW	DEPTH / SWE	2012	2017	HOURLY	AUTOMATIC	Yukon College
FANTAIL UPPER	BC	FANTUPP	DEPTH / SWE	2012	2017	HOURLY	AUTOMATIC	Yukon College
LLEWELLYN LOWER	BC	LLEWLOW	DEPTH / SWE	2013	2017	HOURLY	AUTOMATIC	Yukon College
LLEWELLYN UPPER	BC	LLEWUPP	DEPTH / SWE	2013	2016	HOURLY	AUTOMATIC	Yukon College
WHEATON	YT	WHEATON	DEPTH / SWE	2014	2017	HOURLY	AUTOMATIC	Yukon College

Table 2 introduces the different snow courses for the three watersheds and those snow stations with snow height and snow SWE measurements. Note that the Upper Fantail station was removed from the Upper Yukon River Watershed and relocated within the Mayo Watershed. For the Upper Yukon River Watershed, snow courses prior to 2006 were not included in the database.

The resulting hydrometeorological database for the Mayo, Aishihik and Upper Yukon River Watersheds were then integrated into HYDROTEL. Figure 2.9 presents a screenshot of the three watersheds within the HYDROTEL graphical user interface while Figure 2.10 gives an example of the workspace window for the Aishihik Watershed. The portion of the Aishihik Watershed displayed in beige represents the simulated area and the grey portion, the non-simulated area. It also shows the information menu on the right and the action menu at the top.

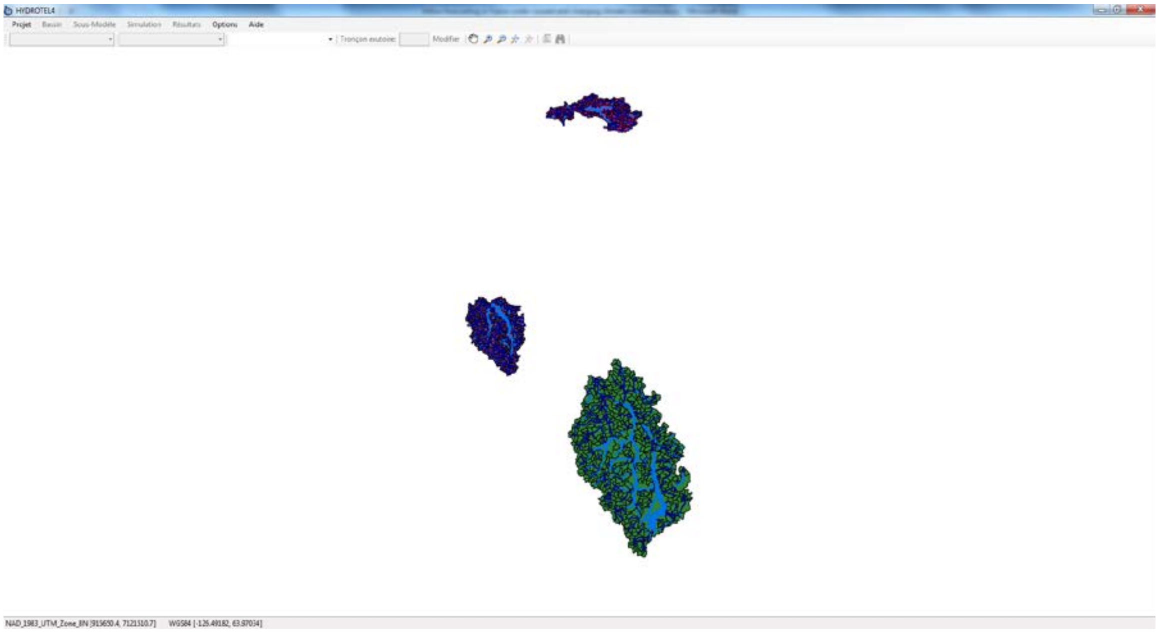


Figure 2.9 Mayo, Aishihik and Upper Yukon River Watersheds displayed using the HYDROTEL graphical user interface.

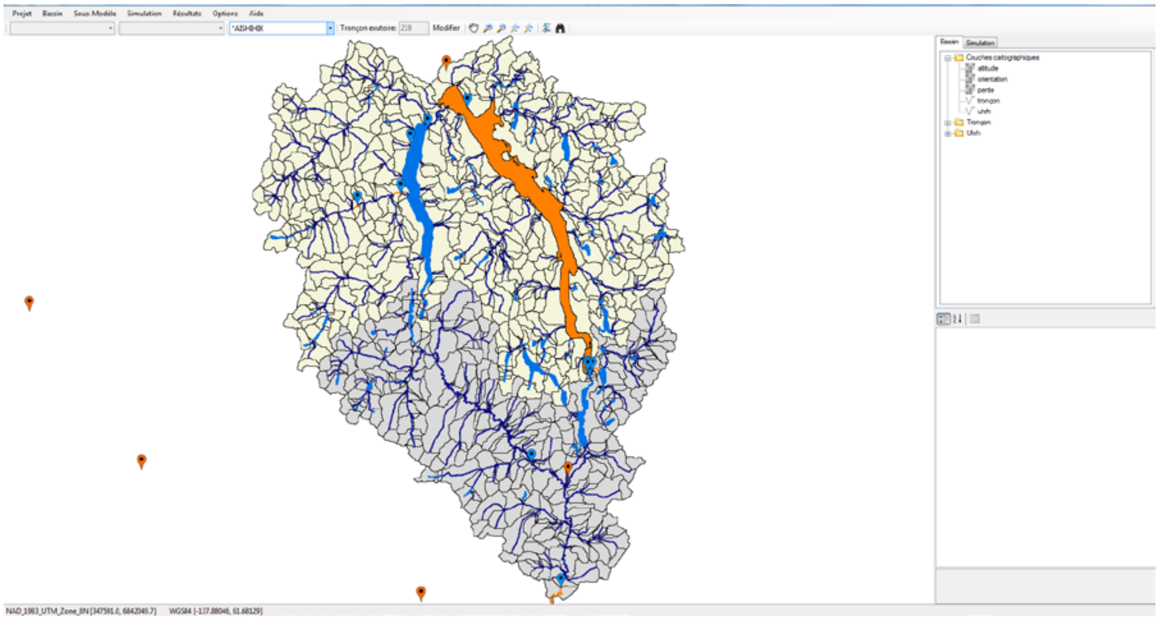


Figure 2.10 Example of workspace window of HYDROTEL.

HYDROTEL models the major physical processes of the water budget using sub-models that include different algorithms or simulation options. As shown in Table 2.8, each sub-model generally offers more than one simulation options.

Table 2.8 HYDROTEL sub-model and simulation Options

Water budget component (sub-model)	Simulation options
1 Interpolation of meteorological data	1.1 Thiessen polygons
	1.2 **Weighted mean of nearest three stations**
2 Snow accumulation and melt	2.1 **Mixed (degree-day) energy-budget method**
	2.2 *Multi-layer model**
3 Soil temperature and soil freezing	3.1 Rankinen
	3.2 Thorsen
4 Glacier dynamics	*4.1 Glacier model**
5 Potential evapotranspiration	5.1 Thornthwaite
	5.2 Linacre
	5.3 Penman
	5.4 Priestley-Taylor
	5.5 Hydro-Québec
	5.6 **Penman-Monteith**
6 Vertical water budget	6.1 **BV3C**
	6.2 CEQUEAU (modified)
7 Overland water routing	7.1 **Kinematic wave equation**
8 Channel water routing	8.1 **Kinematic wave equation**
	8.2 Diffusive wave equation

* Model and simulation option to be developed as part of the current project.

In the above table, the bold face nouns represent the simulation option used for hydrological simulation.

Model calibration and results

Calibration of the model parameters was done by comparing simulated and measured streamflows or simulated and reconstructed reservoir/lake inflows or any relevant state variables (*e.g.*, SWE) for the 2010-2016 period. The calibration involved adjusting the sub-model parameter values in order to corroborate as much as possible with stream flow measurements or lake inflows using an objective function. The result is an optimized set of parameter values that are identical for all RHHUs for the whole watershed (Mayo, Upper Yukon River) or large number of RHHUs. This does not mean that everything is identical for each one of those units, as the hydraulic characteristics on each unit depend on soil type, which are different from unit to another, for instance.

Since model calibration for the Aishihik and Mayo Watersheds relies heavily on the reconstructed reservoir/lake inflows, it seems important to describe the methodology and the equation currently used to determine them.

The general water budget equation for a reservoir or a lake can be expressed as follows:

$$\Delta V = IN + P - E - Q_{out} \tag{1}$$

Where:

ΔV = variation of lake or reservoir volume (*V*) between time (*j*-1) and (*j*) (m^3/s);

IN = sum of inflows from upstream rivers and surrounding hillslopes;

P = precipitation on the surface of the lake or reservoir;

E = evaporation from the surface of the lake or reservoir;

Q_{out} = sum of the entire lake or reservoir outflows.

For both Aishihik and Mayo, P and E were not considered since they can be assumed to be similar over time. Only ΔV and Q_{out} need to be determined to estimate IN as the total inflow.

For both watersheds, we adopted a calculation procedure based on the three-day water level average, thus:

$$\Delta V = V_j - V_{j-1} \tag{2}$$

For Aishihik Lake the general volume calculation is as follows:

When L < 915

$$V = -38627.31L^6 + 678170.61L^5 - 3270008.00L^4 + 6352008.56L^3 - 3111511.38L^2 + 134383853.50 \tag{3}$$

When L >= 915

$$V = -50827494.83L^4 + 731085628.63L^3 - 3932429415.76L^2 + 9545583654.41L - 8448705648.59 \quad (4)$$

Where L represents the water level of water recorded at *Aishihik Lake near Whitehorse* hydrometric station (08AA005). Note that the record at the (08AA005) station must be cumulated to the reference water level (911.565) in order to have the proper water level for the volume calculation in Equations (3) and (4). The results of Equation (4) need to be multiplied by 3600 to get a daily volume.

For Mayo Lake the general volume calculation is as follows:

$$V = \frac{(L-660)}{0.00003814} * 3600 \quad (5)$$

Here L represents the water recorded at the *Mayo Lake near the outlet* hydrometric station (09DC005). Note that the record at the (09DC005) station must be cumulated to the reference water level (662.337) in order to have the proper water level for the volume calculation in Equation (5). To calculate volume variations based on the average water level of the last three days, L in Equations (3) to (5) are calculated as follows:

$$L = \frac{L_j + L_{j-1} + L_{j-2}}{3} \quad (6)$$

Where:

L_j , L_{j-1} and L_{j-2} represent the daily mean water level at the reference hydrometric station for the current day (*j*), previous day (*j*-1) and two day prior (*j*-2).

Before determining the total inflow (IN) in Equation (1), the volume variation must be divided by 86400 s/day to get the flow units (m³/s).

To determine Q_{out} for Aishihik Lake, we used the following equation:

$$Q_{out} = Q_{08AA010} - Q_{08AA009} \quad (7)$$

Where:

$Q_{08AA010}$= The average daily flow at the *Aishihik River below Aishihik Lake* hydrometric station (08AA010);

$Q_{08AA009}$= The average daily flow at the *Giltana Creek near the mouth* hydrometric station (08AA009).

To calculate the most accurate lake outflow, we need to subtract the Giltana Creek (08AA009) flow from the Aishihik River measurements since the (08AA010) hydrometric station is located downstream of both Aishihik Lake and Giltana Creek and is the closest flow measurement downstream of the Lake.

To determine Q_{out} for Mayo Lake, we use the following equation:

$$Q_{out} = Q_{YECMAYO} \quad (8)$$

Where:

$Q_{YECMAYO}$= The average daily flow measurement made by YEC at the outlet of the Mayo Lake facility.

As the volume variation ΔV is calculated between the current day (*j*) and the previous day (*j*-1) the Q_{out} value in Equation (1) must be calculated as follows:

$$Q_{out} = \frac{Q_{out,j} + Q_{out,j-1}}{2} \quad (9)$$

Where $Q_{out,j}$ and $Q_{out,j-1}$ represent for both watersheds the outflow (Equations 6 & 7) for the current day (*j*) and the previous day (*j*-1).

For both watersheds, a particular case must be addressed to ensure proper calculation of the total daily average inflow.

For Aishihik, measurements at the Giltana Creek hydrometric station (08AA009) are missing sometimes. Under such circumstances, a precise procedure was developed by YEC to correct flow measurements at the Aishihik River station (08AA010) and it can be accounted for using a specific equation.

When $Q_{08AA009}$ is missing, the correction applied to the $Q_{08AA010}$ measured flow is given by the general linear regression:

$$Q_{08AA010} = m_{(month)} Q_{08AA010} + b_{(month)} \quad (10)$$

Where $m_{(month)}$ and $b_{(month)}$ represent the slope and the intercept of the linear regression equation calculated for every month of the year. The monthly values of m and b are introduced in Table 2.9.

Table 2.9 Monthly values of slope and intercept of the linear regression equation to estimate the Aishihik River station (08AA010) flows when measurements at the Giltana Creek hydrometric station (08AA009) are missing.

Month	m	b
1	0.995	-0.048
2	0.997	-0.046
3	0.999	-0.055
4	0.990	-0.102
5	0.869	-1.070
6	0.822	-0.576
7	0.980	-0.592
8	0.957	-0.193
9	0.959	-0.352
10	0.978	-0.416
11	0.995	-0.266
12	0.992	-0.093

It is important to highlight that for both watersheds, the estimated total inflows may result in a negative value. This is known as a false negative value, because the water budget equation assumes a horizontal surface. However, large Lakes act as large mechanical oscillator driven by wind forces, precipitations, ice, water management etc… Such conditions can result in errors in total inflow calculation; including excessive variations and negative values (Perreault, 1995). In the case of negative inflow values, it was decided to substitute the negative values by a nominal value.

Also for Aishihik it was also proposed to use the *Sekulmun River at the outlet of the Sekulmun Lake* hydrometric station (08AA008) flow measurements as an option to correct the negative inflow results.

For Aishihik Lake:

When IN < 0.0m³/s then $IN = 0.01\ or\ Q_{08AA008}$

For Mayo Lake:

When IN < 0.0m³/s then $IN = 0.01$

The nominal values for Aishihik Lake and Mayo Lake correspond to the minimum positive inflow calculated for the entire historical period available.

Throughout the calibration procedure of HYDROTEL, model performance with respect to corroborating with measured flows or reconstructed inflows was evaluated using different criteria.

1. A visual inspection of the graphical representation of observed and simulated flows;

2. The Nash-Sutcliffe criterion calculated with the following equation:

$$NS = 1 - \frac{\sum_{i=1}^{n}(Q_{obs} - Q_{sim})^2}{\sum_{i=1}^{n}\left(Q_{obs} - Q_{obs,mean}\right)^2} \quad (11)$$

Where Q_{obs} represents the observed flow or reconstructed inflow, Q_{sim} the simulated flow or inflow, $Q_{obs,mean}$ the mean observed flow or reconstructed inflow from day 1 to (*n*) number of days (daily time step).

The value of the criterion ranges from (-∞ to 1.0) where one (1) represents the optimum. This criterion evaluates the amplitude and the synchronism between observed and simulated flows or inflows. Generally, this criterion is highly influenced by the presence and representation of the peak freshet that makes it less adapted for a long low flow period;

3. The observed and simulated annual runoff (water volume / watershed area) can be used to compare water volumes based on the following equation:

$$Runoff_{year} = \frac{\sum_{i=1}^{n}(Q\ x\ CONV)}{AREA} \quad (12)$$

Where $Runoff_{year}$ represents the annual runoff expressed in (mm), Q the observed or simulated flow or inflow (m³/s), $AREA$ the drainage area upstream of the comparison site (km²) and CONV a conversion factor to respect the proper unit (mm) of the resulting annual runoff;

4. The PBIAIS criterion (bias percentage) that is calculated with the following equation:

$$PBIAIS = \frac{\sum_{i=1}^{n}(Q_{sim} - Q_{obs})}{\sum_{i=1}^{n} Q_{obs}} \ x\ 100 \qquad (13)$$

This criterion, expressed in (%), can be used to quantify the bias between simulated and observed values. The value of the criterion varies between (-∞ to +∞) where zero (0) is the optimum;

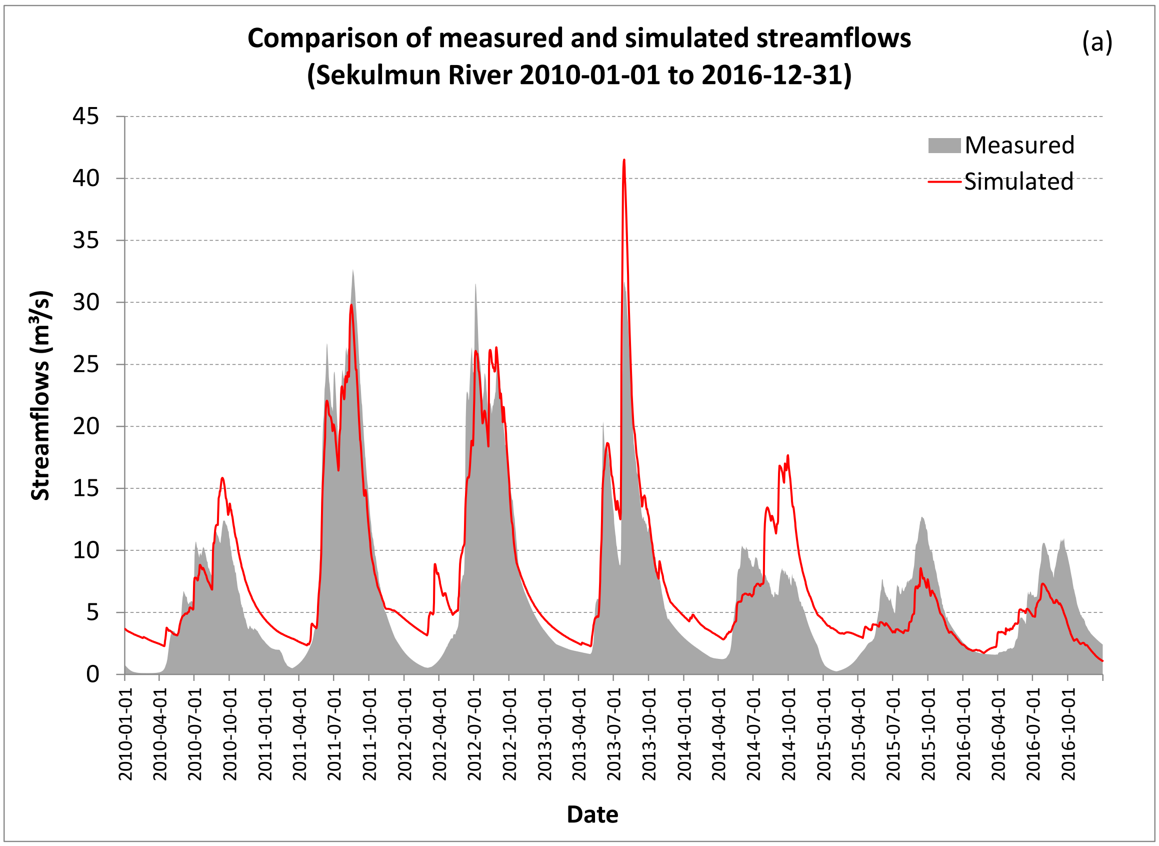
5. Root mean square error (RMSE) that can be calculated as follow:

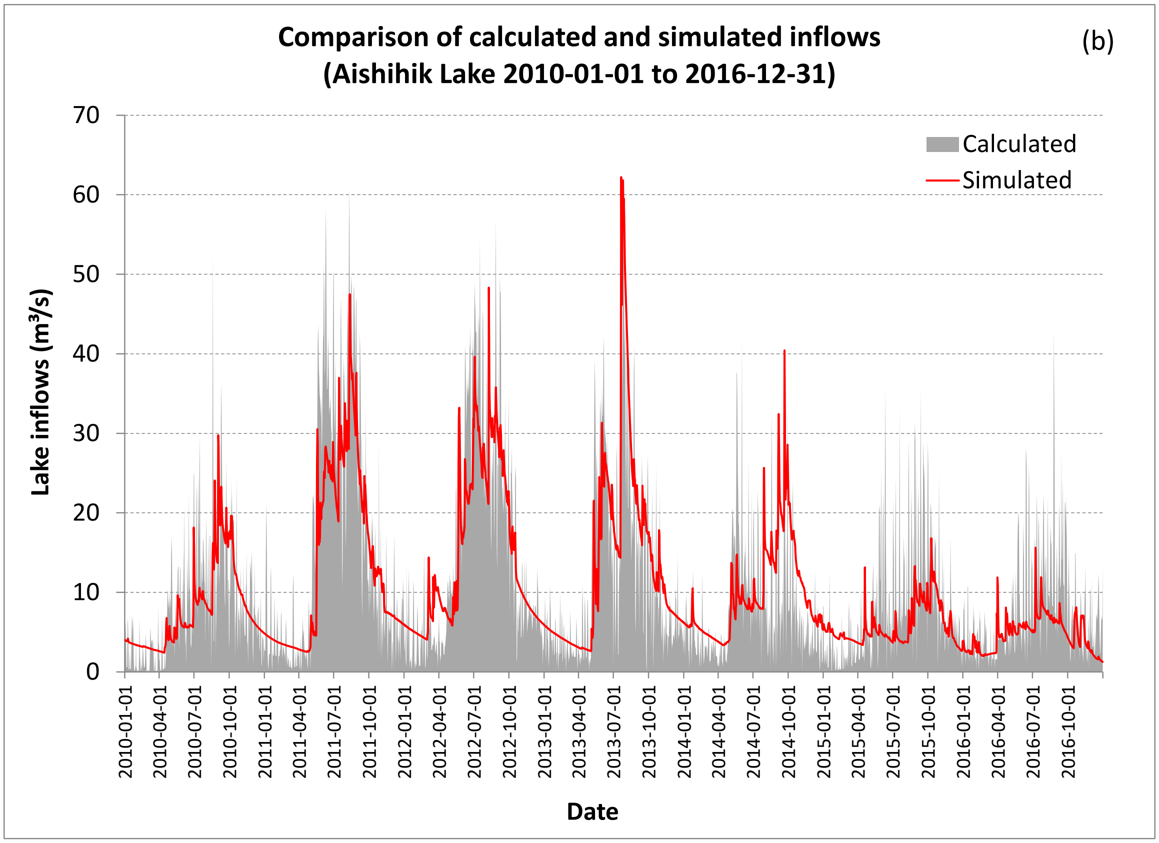
$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Q_{obs} - Q_{sim})^2}{n}} \qquad (14)$$

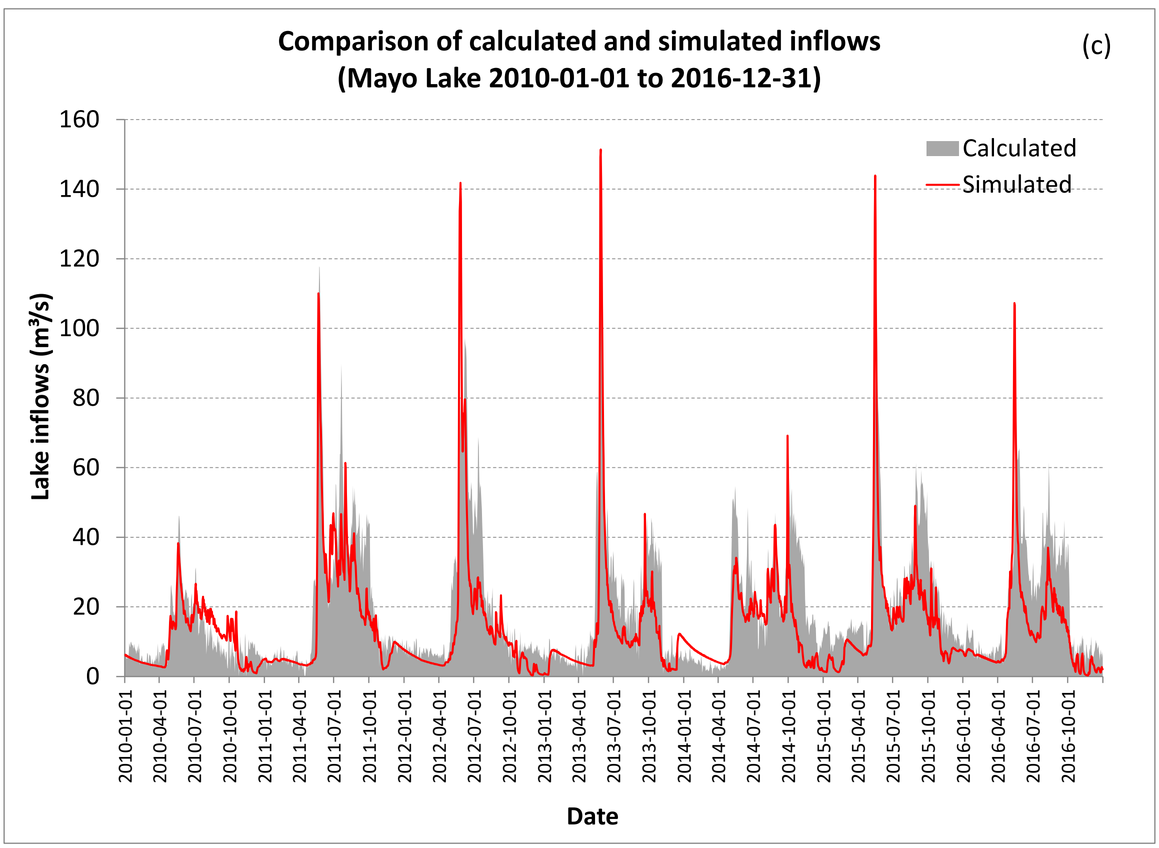
The resulting value of this criterion varies between (0 to +∞) where zero (0) is the optimum. This criterion expressed in m³/s for flows or inflows, assesses the general agreement between observed and simulated flows or inflows. Essentially this criterion is influenced by the largest discrepancies.

Calibration of HYDROTEL was first performed on the Aishihik Watershed using flows measured at the *Sekulmun River at the outlet of the Sekulmun Lake* hydrometric station (08AA008) and reconstructed inflows for Aishihik Lake. Secondly, the model was calibrated on the Mayo Watershed using the reconstructed inflows to Mayo Lake. Finally, a first calibration was performed for the Upper Yukon River Watershed using the flows recorded at the *Yukon River at Whitehorse* hydrometric station (09AB001). Note that at this stage of the project, we have performed a spatial calibration on the Aishihik Watershed with specific model calibration parameters for the entire Sekulmun River Watershed and another set of calibration parameter values for the remaining of the portion of the watershed. For Mayo Lake and Upper Yukon River Watersheds, we have performed a global calibration with unique sets of model parameter values for each watershed. The calibrated models were used as baselines for the development of the data assimilation procedure developed by NCE. The models and data assimilation scheme represent the core of the flow and inflow forecasting system.

The model calibration and the development of the data assimilation procedure for the Aishihik watershed were based on the aforementioned methodology used to reconstruct inflows (i.e., Aishihik Lake). An updated version of the water level/lake water volume relationship (Equations 3 and 4) was proposed mid November 2017. Throughout the calibration process, the Sekulmun River flows were used as inflows for cases where negative reconstructed inflows were obtained. During the first year of the project, it was decided instead that a nominal value would be used to correct the negative reconstructed inflows. As mentioned before, the calibration period ranges from 01/01/2010 to 31/12/2016. Figure 2.11 and Table 2.10 present the calibration results.




Comparison of calculated and simulated inflows
(Aishihik Lake 2010-01-01 to 2016-12-31)
(b)
Calculated
Simulated
Lake inflows (m³/s)
Date


Comparison of calculated and simulated inflows
(Mayo Lake 2010-01-01 to 2016-12-31)
(c)
Calculated
Simulated
Lake inflows (m³/s)
Date

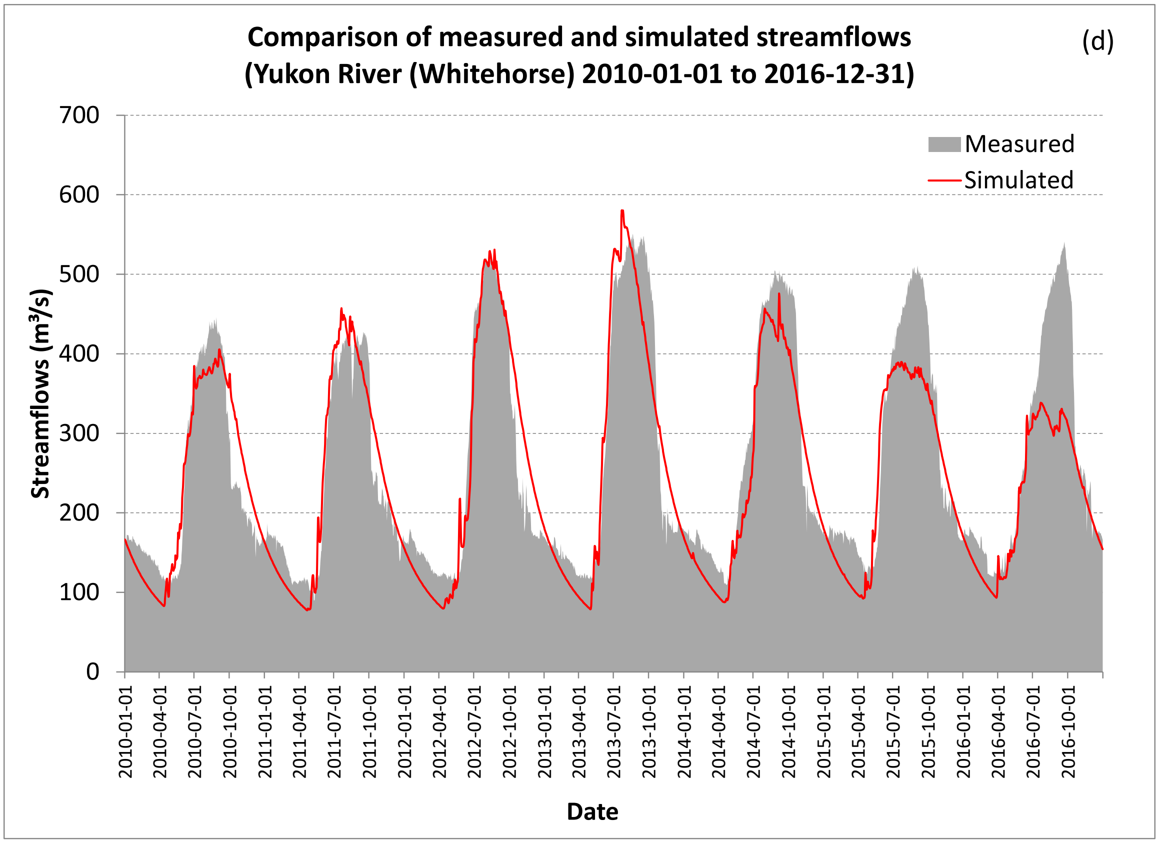


Figure 2.11 Graphical comparisons of measured flows or calculated inflows with simulated flows or inflows for: (a) Sekulmun River, (b) Aishihik Lake, (c) Mayo Lake and (d) Yukon River (Whitehorse).

Table 2.10 Calibration performance in corroborating with observed flows or reconstructed inflows for the 2010-2016 period for each watershed.

Watershed	Site	NS	$Runoff_{year}$ (mm)	$PBIAIS$ (%)	$RMSE$(m^3/s)	Comment*
Aishihik	Sekulmun River	0.84	192 (178)	8.17	2.82	Very Good
	Aishihik Lake	0.61	108 (119)	-8.86	6.95	Adequate
Mayo	Mayo Lake	0.58	253 (358)	-29.38	12.03	Adequate
Yukon	Yukon River (Whitehorse)	0.84	388 (414)	-6.44	54.59	Very Good

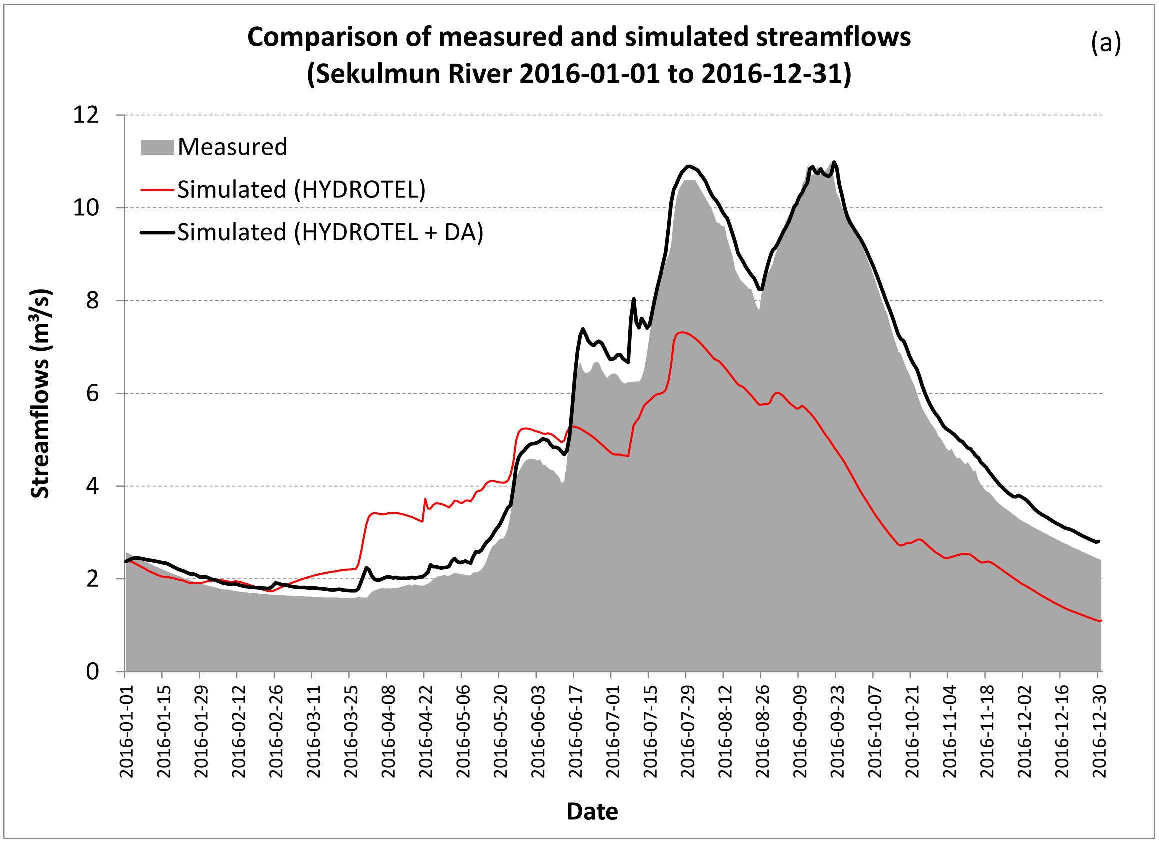
* Based on the work of Moriasi et *al*. (2007)

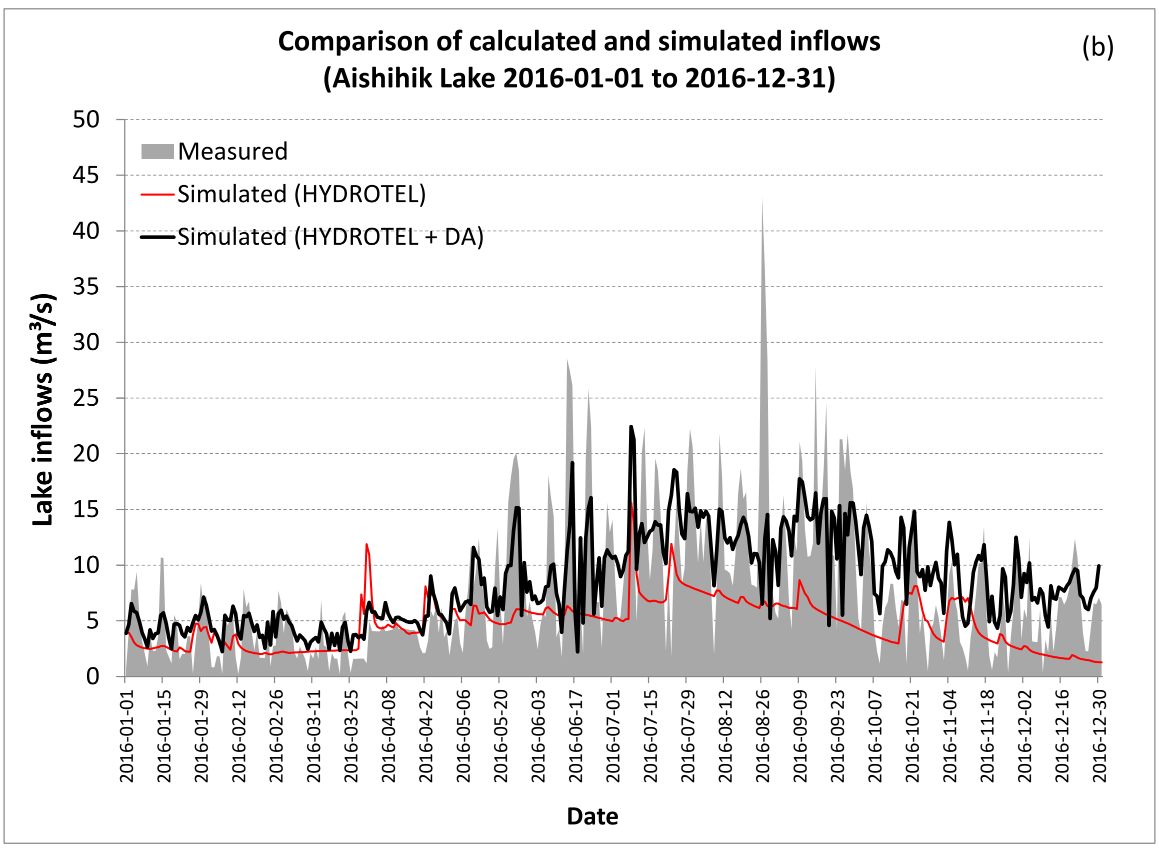
Based on the results introduced in Figure 2.111 and Table 2.10, it can be observed that HYDROTEL performs better given natural or near natural flows as measurements with an overestimation of winter low flows for Sekulmun and underestimation of winter low flows for the Yukon River at Whitehorse. Also for the Yukon River spring freshet of years 2015 and 2016, the flows are clearly underestimated.

It is all likelihood due to an underestimation of the snowpack accumulation by HYDROTEL. For the Aishihik Lake inflows, the model failed to capture important daily variations. However, the model captured well the general shape of the annual hydrograph; although there was an overestimation of the winter low flows. Also the spring freshet for years 2015 and 2016 were underestimated by the model. For the Mayo Lake inflows, again the model captured well the general shape of the annual hydrograph, but clearly underestimated summer and fall peak flows as indicated by the PBIAIS value. Moreover, the Mayo Lake inflows show less daily variations than the Aishihik Lake inflows. Despite these discrepancies, it can be said that HYDROTEL successfully depicts the general shape of the annual hydrograph of each watershed. It remains important to mention that the model is not yet adapted for the Upper Yukon River. Indeed, it does not model explicitly the presence of the glaciers in the south-west mountainous part of the watershed. Glacier melt and mass balance are not accounted for in the model and, thus, the model underestimates the runoff associated with the melting. As glacier melt processes are very slow, he model can still be used to produce daily forecast, but not readily used for long term or even seasonal forecast. That being mentioned, this project will integrate in the second year a simple glacier module into HYDROTEL so the model can be used for seasonal forecasting. At this stage of the project, the model is only used in a forecasting mode on the Aishihik and Mayo Watersheds. Calibrated models for Aishihik and Mayo were shared with our colleagues at NCE to develop the data assimilation scheme.

2.2.4. Impact of data assimilation

In this section, all the results pertaining to the data assimilation scheme where provided by NCE. In general, data assimilation consists in correcting the values of the model state variables in order to reproduce either the simulated flows or the calculated inflows. The method was developed using the 2016 hydrometeorological data. The procedure was developed and applied using a daily time step correcting for each day the simulated hydrological state variables to improve the upcoming flows or calculated inflows. Figure 2.12 and Table 2.11 illustrates the type of improvement that can be achieved for the Sekulmun River flows, Aishihik Lake inflows and Mayo Lake inflows for the year 2016.


Comparison of measured and simulated streamflows
(Sekulmun River 2016-01-01 to 2016-12-31)
(a)
Measured
Simulated (HYDROTEL)
Simulated (HYDROTEL + DA)
Streamflows (m³/s)
0
2
4
6
8
10
12
Date
2016-01-01
2016-01-15
2016-01-29
2016-02-12
2016-02-26
2016-03-11
2016-03-25
2016-04-08
2016-04-22
2016-05-06
2016-05-20
2016-06-03
2016-06-17
2016-07-01
2016-07-15
2016-07-29
2016-08-12
2016-08-26
2016-09-09
2016-09-23
2016-10-07
2016-10-21
2016-11-04
2016-11-18
2016-12-02
2016-12-16
2016-12-30


Comparison of calculated and simulated inflows
(Aishihik Lake 2016-01-01 to 2016-12-31)
(b)
Measured
Simulated (HYDROTEL)
Simulated (HYDROTEL + DA)
Lake inflows (m³/s)
0
5
10
15
20
25
30
35
40
45
50
Date
2016-01-01
2016-01-15
2016-01-29
2016-02-12
2016-02-26
2016-03-11
2016-03-25
2016-04-08
2016-04-22
2016-05-06
2016-05-20
2016-06-03
2016-06-17
2016-07-01
2016-07-15
2016-07-29
2016-08-12
2016-08-26
2016-09-09
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2016-10-07
2016-10-21
2016-11-04
2016-11-18
2016-12-02
2016-12-16
2016-12-30

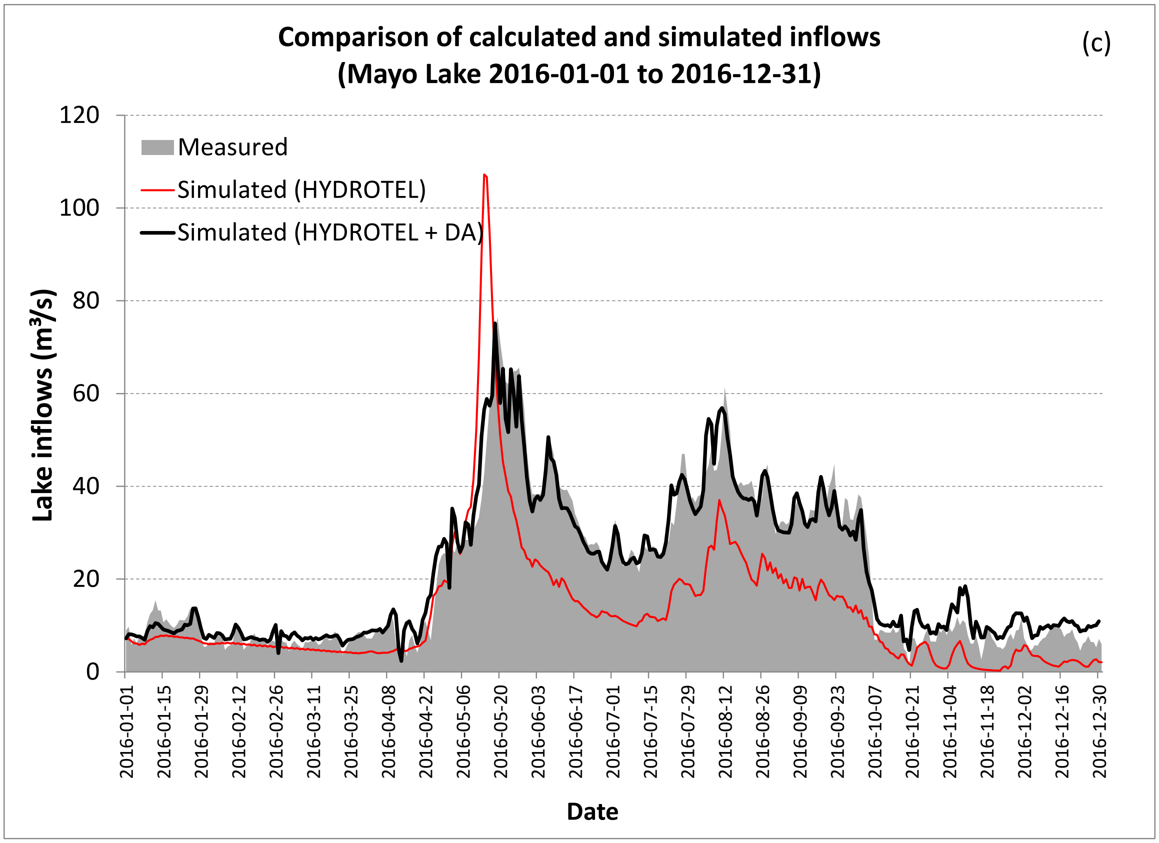


Figure 2.12 Graphical comparisons of measured flows or calculated inflows with simulated flows and inflows following data assimilation (DA) for: (a) Sekulmun River, (b) Aishihik Lake and (c) Mayo Lake.

Table 2.11 Model performance in representing observed flows or inflows for the 2016 year.

Watershed	Site	NS	$Runoff_{year}$ (mm)	$PBIAIS$ (%)	$RMSE$(m³/s)	Remarks
Aishihik	Sekulmun River	0.42	92 (122)	-24.37	2.36	Poor
		0.99	130 (122)	6.00	0.37	Very good
	Aishihik Lake	-0.04	51 (83)	-38.97	6.95	Unsatisfactory
		0.49	91 (83)	10.20	4.54	Poor
Mayo	Mayo Lake	0.34	235 (381)	-38.22	13.59	Poor
		0.95	390 (381)	2.41	3.64	Very good

(Red characters stand for HYDROTEL results and Black characters stand for HYDROTEL + Data assimilation results)

As indicated, data assimilation provides a clear enhancement of the representation of the Sekulmun River flows and the Mayo Lake inflows with nearly perfect fits. For the Aishihik Lake inflows, data assimilation offers an interesting gain in model performance, but the combination of HYDROTEL and DA has yet to capture the daily variations of the calculated inflows. Nonetheless, these results are promising and build our confidence to deliver robust daily forecast flows for Sekulmun River flows and Mayo Lake inflows as well as relevant shapes of hydrographs for Aishihik Lake inflows.

2.2.5. Challenges and potential solutions

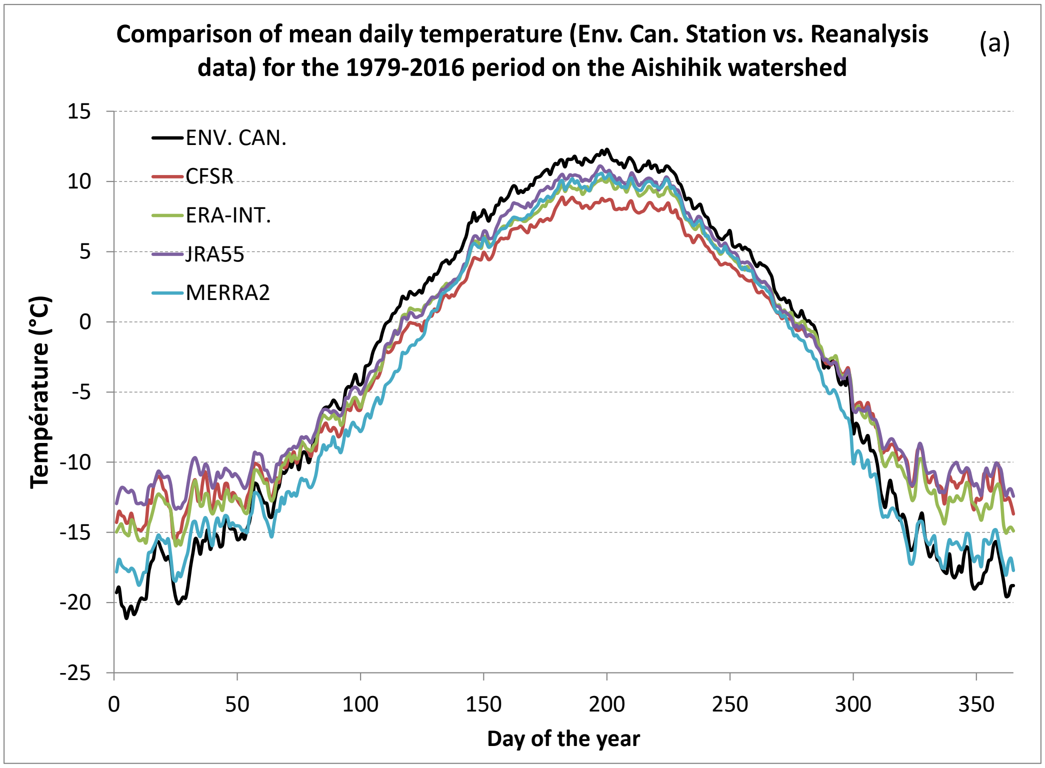
The first results show good performances in the representation of the flows at Sekulmun and inflows at Mayo Lake, future work should focus on improving the results for the inflows at Aishihik Lake. As mentioned before, calculation of inflows for the Aishihik Lake is associated with non negligible uncertainties related to the measurements of numerous independent variables such as the water level; the flows of the Aishihik River downstream of Aishihik Lake and the flows of the Giltana Creek. Efforts should be made to improve the robustness of the measurements prior to calculating inflows.

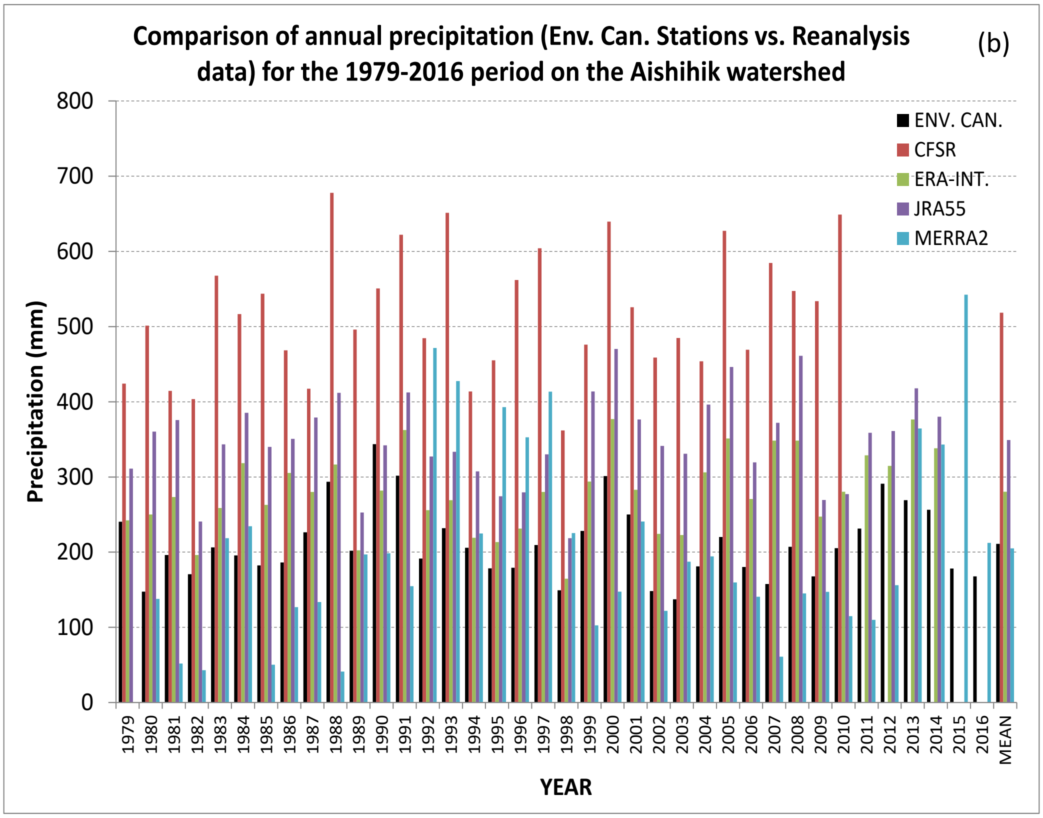
For both Aishihik and Mayo Watersheds, operational meteorological stations surrounding or within the watershed boundaries are limited and efforts are currently made to improve these limitations. Adding meteorological stations would certainly further improve the forecasting system performance for the coming years as recommended to YEC in the technical note (Strategic planning of meteorological and snow monitoring stations – Case of the Mayo watershed) produced by Rousseau and Savary (2017).

For the Upper Yukon River Watershed, future work will include the development and integration of a glacier module to HYDROTEL. We will examine the possibility of integrating this third basin in the forecasting system. This would require the development of a data assimilation procedure adapted to this specific watershed.

2.2.6. Reanalysis data

During the calibration of HYDROTEL, we investigated the use of reanalysis data for Aishihik and Mayo; that is CFSR (Saha et *al.*, 2010), ERA-Interim (Dee et al., 2011), MERRA2 (Rienecker et *al*., 2011], JRA55 (Kobayashi et *al*. 2015) data were considered. This investigation turned to be non-conclusive. Indeed, the meteorological conditions (precipitations) proposed by the diverse reanalysis datasets did not corroborate very well with the observed conditions (see Figure 2.13). Given this outcome, it would not have been consistent to calibrate HYDROTEL with any of the aforementioned reanalysis data.




Comparison of annual precipitation (Env. Can. Stations vs. Reanalysis data) for the 1979-2016 period on the Aishihik watershed
(b)
ENV. CAN.
CFSR
ERA-INT.
JRA55
MERRA2
Precipitation (mm)
YEAR
0
100
200
300
400
500
600
700
800
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
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2002
2003
2004
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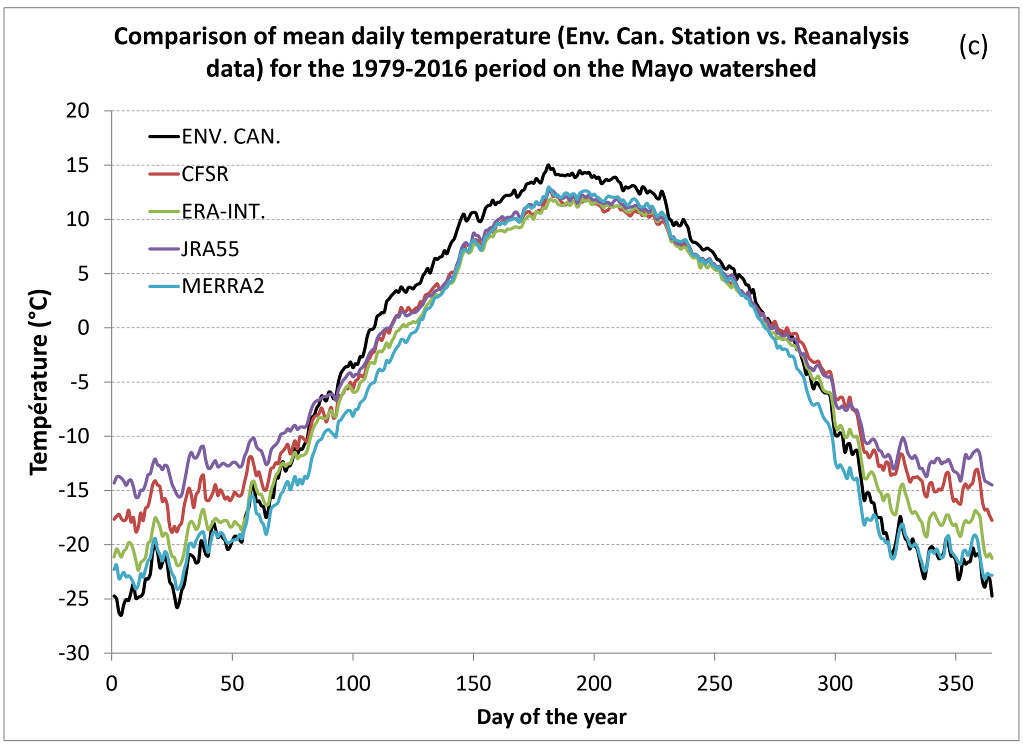
2010
2011
2012
2013
2014
2015
2016
MEAN


Comparison of mean daily temperature (Env. Can. Station vs. Reanalysis data) for the 1979-2016 period on the Mayo watershed
(c)
ENV. CAN.
CFSR
ERA-INT.
JRA55
MERRA2
Température (°C)
Day of the year
20
15
10
5
0
-5
-10
-15
-20
-25
-30
0
50
100
150
200
250
300
350

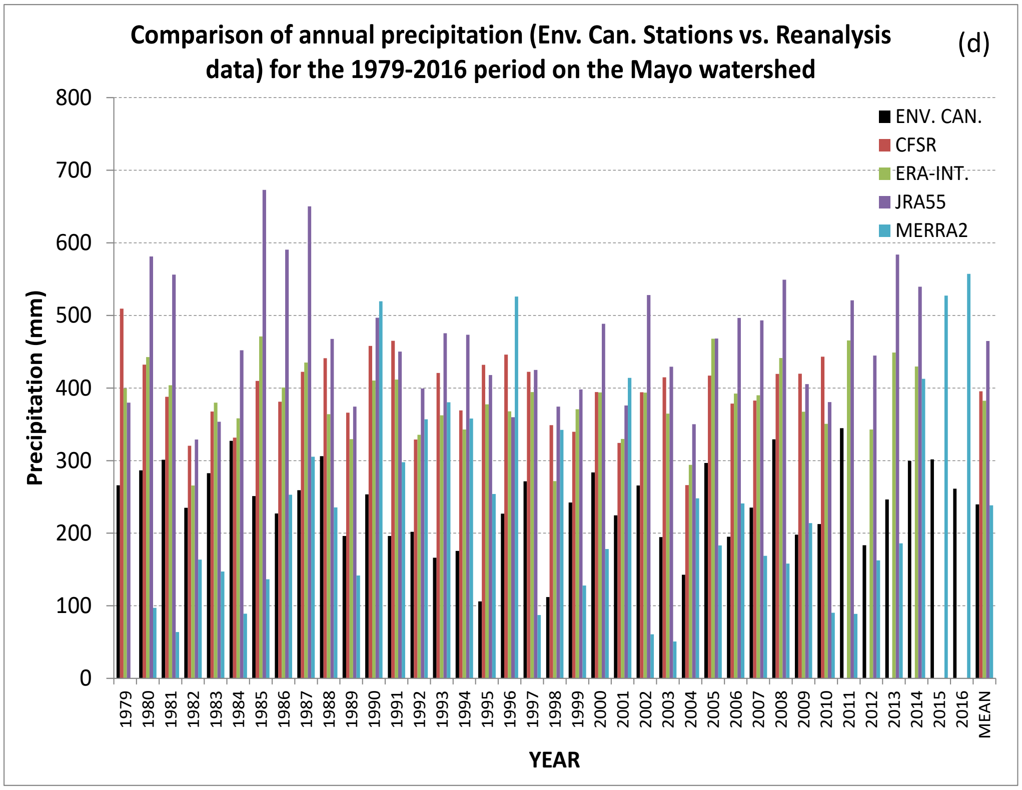


Figure 2.13 Comparison of observed (Environment Canada) and reanalysed (CFSR, ERA-INT, JRA55, MERRA2) mean daily temperature and total annual precipitation at the scale of the Aishihik and Mayo.

Figure 2.13 illustrates clear tendencies that can be summarized as follows:

1. For both Aishihik and Mayo, summer temperatures from reanalysis data underestimate observed temperatures. On the opposite, winter temperatures from reanalysis data mainly overestimate those observed.

2. Total annual precipitations from CFSR, ERA-INT and JRA55 systematically overestimate those observed precipitations for both watersheds - except for year 1990 for ERA-INT and JRA55 in the case of the Aishihik Watershed. For Aishihik, the ratio of reanalysed over observed total annual precipitations for CFSR, ERA-INT and JR55 are 2.6, 1.4, 1.7 and for Mayo 1.8, 1.7, 2.1. Even if the ratio is very close to one (1.0) for MERRA-2, the correlation remains very low for all series for both watersheds. For Aishihik, the coefficient of determination for CFSR, ERA-INT, JRA55 and MERRA-2 are 0.23, 0.33, 0.23, 0.00, respectively and for Mayo 0.04, 0.36, 0.16, 0.04.

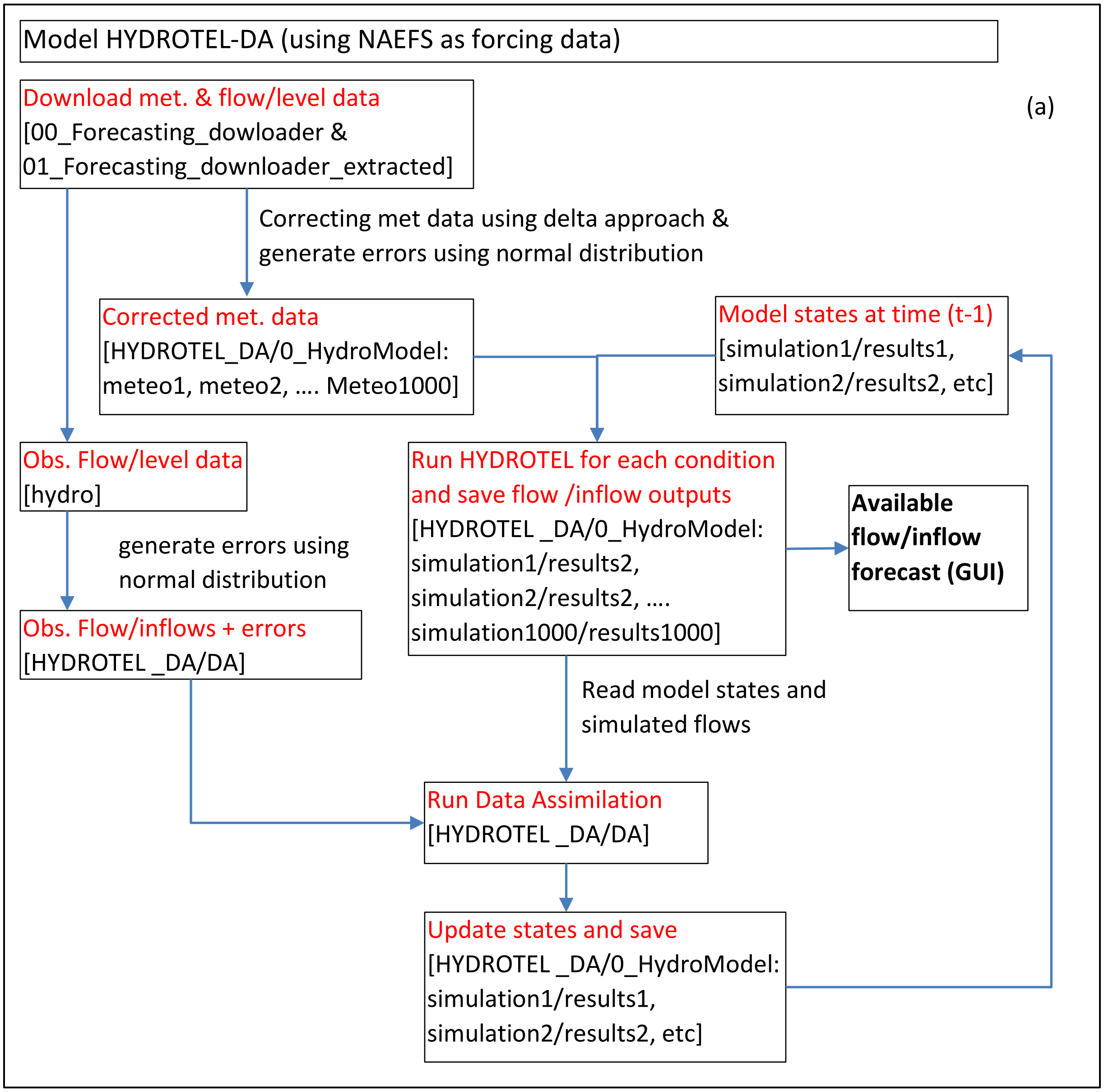
Based on such observations, the reanalysis data could not be considered as reliable data for model calibration in the current context and further development of the forecasting system.

2.3. Forecasting system

At first it is important to mention that the development of the forecasting system is joint venture between INRS and NCE. The forecasting system regroups four major components: (1) the data manager component; (2) the HYDROTEL model; (3) the data assimilation scheme and (4) the graphical user interface (GUI).

The system operates under two specific meteorological forecast ensembles: the North American Ensemble Forecast System (NAEFS) issued by the Meteorological Service of Canada (MSC) for the 1 to 14 days weather forecast and ECCC's seasonal forecasting system CanSIPS for longer lead times (*i.e.*, seasonal flows or inflow forecasts; 1 to 12 months).

Figure 2.14 provides an overview of the flow/inflow forecasting system including: (a) NAEFS and (b) CanSIPS meteorological ensemble forecast. Both flow charts where provided by NCE.


Model HYDROTEL-DA (using NAEFS as forcing data)
(a)
Download met. & flow/level data
[00_Forecasting_dowloader &
01_Forecasting_downloader_extracted]
Correcting met data using delta approach &
generate errors using normal distribution
Corrected met. data
[HYDROTEL_DA/0_HydroModel:
meteo1, meteo2, …. Meteo1000]
Model states at time (t-1)
[simulation1/results1,
simulation2/results2, etc]
Obs. Flow/level data
[hydro]
Run HYDROTEL for each condition
and save flow /inflow outputs
[HYDROTEL _DA/0_HydroModel:
simulation1/results2,
simulation2/results2, ….
simulation1000/results1000]
Available
flow/inflow
forecast (GUI)
generate errors using
normal distribution
Obs. Flow/inflows + errors
[HYDROTEL _DA/DA]
Read model states and
simulated flows
Run Data Assimilation
[HYDROTEL _DA/DA]
Update states and save
[HYDROTEL _DA/0_HydroModel:
simulation1/results1,
simulation2/results2, etc]

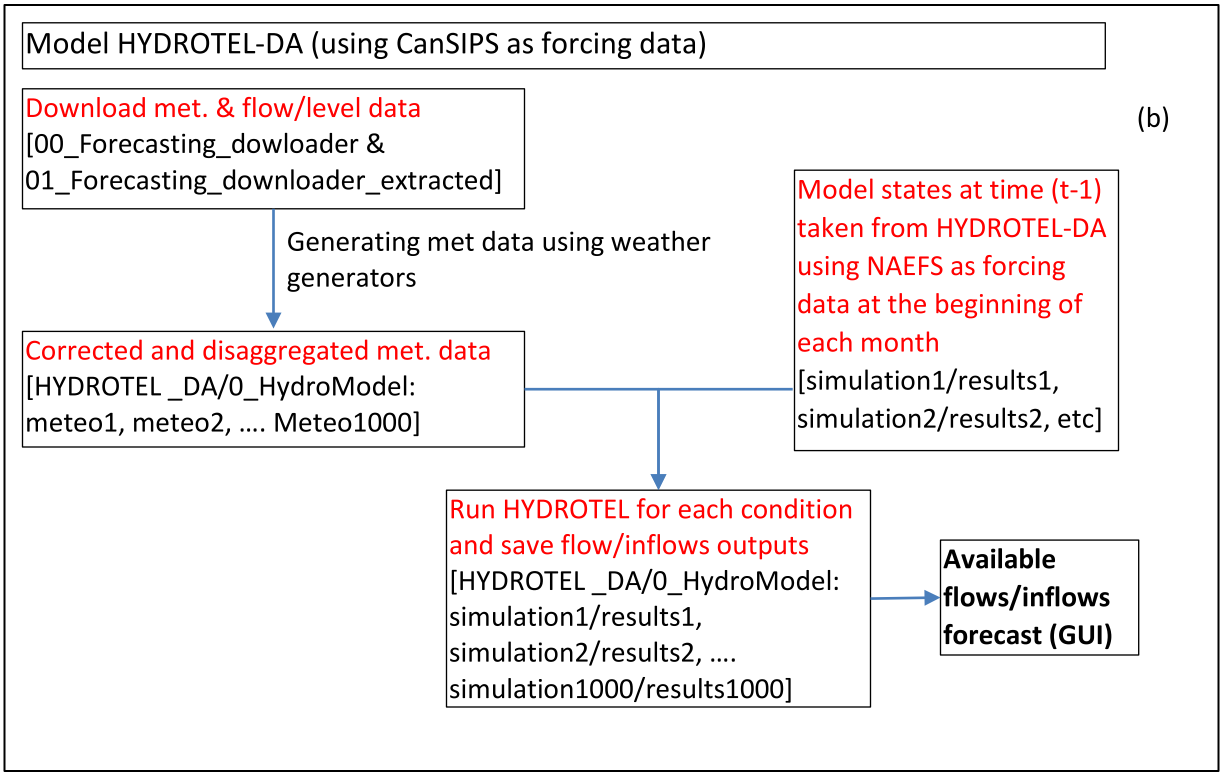


Figure 2.14 Forecasting system flow chart (including working directory) for both NAEFS (a) and CanSIPS (b) meteorological forecasting ensembles.

The forecasting system operates in a step-by-step fashion as follows:

1. Automatic download and update of the hydro-meteorological data recorded by the meteorological and hydrometric stations; including flows and water level. Also the user can update manually the required data; including snow course measurements;

2. Automatic download and correction of the NAEFS meteorological ensemble forecast and, if available, download correction and disaggregation of CanSIPS meteorological ensemble forecast. CanSIPS data are monthly values that need to be timely downscaled to daily value in order to be used with HYDROTEL. The time-downscaling procedure uses a weather generator developed by NCE.

3. Errors are added to recorded hydrometric data and weather forecast data in order to produce multiple hydrological simulations and state variable values including simulated flows/inflows.

4. For NAEFS, the data assimilation is first applied on the previous day simulated hydrological state variables. This procedure attempts to correct and update the previous day simulated state variables to better represent the corresponding flows or calculated inflows. Updated and corrected previous day hydrological state variables then act as initial conditions for the current day and following forecast.

5. Run HYDROTEL in a forecast mode using the initialized ensembles of hydrological state variables with the ensemble of meteorological forecast to get flow/inflow forecasts. For CanSIPS monthly forecast, the initial conditions correspond to the NAEFS corrected hydrological state variables conditions saved at the end of the previous month. Note that CanSIPS forecasts are updated at the beginning of each month.

6. The graphical user interface displays historical results from the coupled HYDROTEL-Data assimilation procedure and measured flows or calculated inflows as well as forecasted inflows/ flows based on NAEFS or CanSIPS ensemble forecast.

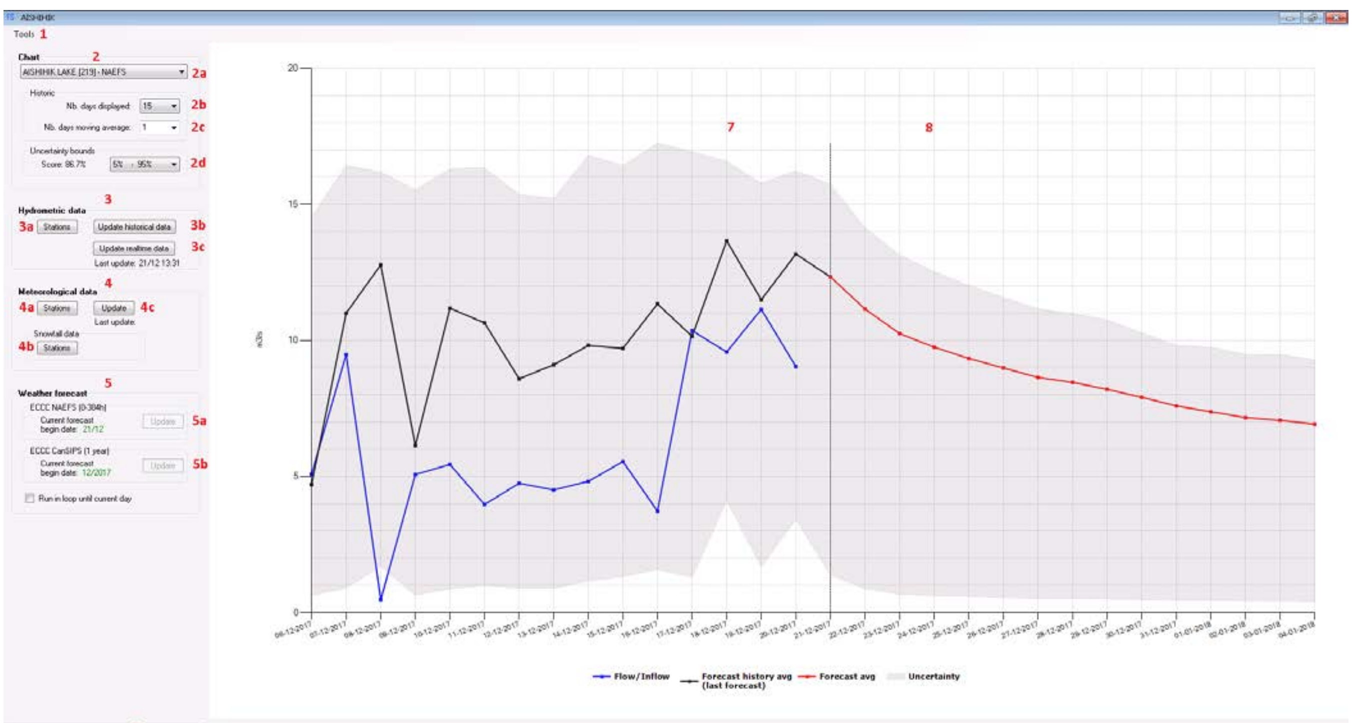


Figure 2.15 Print screen of the hydrological forecast system GUI.

The following list describes the hydrological forecast system GUI using the annotated numbers (see Figure 2.15).

1. The Tools menu gives a direct access to the task manager governing the system automatic download and application.

2. Chart section: this section regroup the different available functions linked to the generated chart.

   2a. Selection box of the available forecast for the current project (watershed) (ex: Sekulmun River, or Aishihik Lake inflows for the Aishihik Watershed).

   2b. Number of displayed previous days for NAEFS (15, 30, 90, 180, 365, ALL) or months for CanSIPS (12, 24, ALL).

   2c. Numbers of consecutive days used in the calculation of the moving average of forecasted flows/inflows in the historical portion of the graph. Note that this number does never affect the number of days used for daily inflow calculation.

   2d Selection box of the illustrated uncertainty bounds (2.5-97.5%, 5-95%, 10-90%, 25-75%.).

3. Hydrometric (a.k.a. hydrological) data section: this section regroups the available operations related to hydrometric data including calculated lake inflows.

   3a. The station button gives access to the list of hydrometric stations. By clicking on any station included in the list, the user can then modify and update manually the hydrometric records (flows, water level, lake inflows). Stations can also be added or removed from the list.

   3b. The historical update button allows for a complete download and update of any new or existing hydrometric stations included in the list. Note that this process can take several minutes to complete and overwrite existing data.

   3c. The real-time update button provides a way for the user to force the update of the hydrometric data. Only the last 30 days are updated and existing data are overwritten. The real-time update is performed when setting the automatic hydrometric data update. Note that the system displays under the button the date and time of the last update.

4. Meteorological data section: this section regroups the available operations related to meteorological data including measured snow data.

   4a. The station button gives an access to the list of meteorological stations. By clicking on any station of the list, the user can then modify and update manually the meteorological records. Stations can also be added or removed from the list. It is possible to search and add stations directly from the Environment Canada website. Stations are searched with a radius parameter.

   4b. The snow station button gives access to the list of snow course stations. By clicking on any station of the list, the user can then modify and update manually the snow conditions. Note that the forecast system cannot automatically update the snow data and the user must add new data manually when such data are available;

   4c. The update button allows for the user to force the update of the meteorological data. Note that the system automatically updates the data and the date and time of the last update are shown under the button;

5. Weather forecast section: this section regroups the two options currently available for the forecasting system;

   5a. The Upper update button allows for the user to update manually the NAEFS meteorological ensemble forecast. Note that if the system had automatically updated the data, the button is not available. Also, on left of the button there is a date that indicates the current (last performed) forecast of the system. The date represents the beginning date of the forecast. The green color indicates that the system is up to date while the red color indicates that the system is outdated. Note that in this case, a manual update of the NAEFS data file may be needed as the data may be no longer available on the Environment Canada website.

5b. The lower update button provides a way to the user to update manually the CanSIPS meteorological ensemble forecast. Note that if the system had automatically updated the data, the button is not available. Again, to the left of the button, there is a date that indicates the current (last performed) forecast of the system. The date represents the beginning date of the forecast. The green color indicates that the system is up to date while the red color indicates the system is outdated. Note that in this case, a manual update of the CanSIPS data file may be needed as the data may be no longer available on the Environment Canada website. As a reminder the CanSIPS forecast are only renewed at the beginning of each month. Thus, running the forecast past the beginning of the month will end up with results identical to those obtained at the beginning of the month.

6. This lower inscription displays the last system activity log or message. By clicking on the text, a window displays the history of the activity log and related detailed messages. These data are saved in the `activity_log.txt` file in the `FS` subfolder of the HYDROTEL project folder.

7. This annotation only indicates the historical part of the graphic including flows or calculated inflows and simulated/corrected flows or inflows with uncertainties.

8. This annotation identifies the forecast portion of the graphic depicting uncertainty bounds.

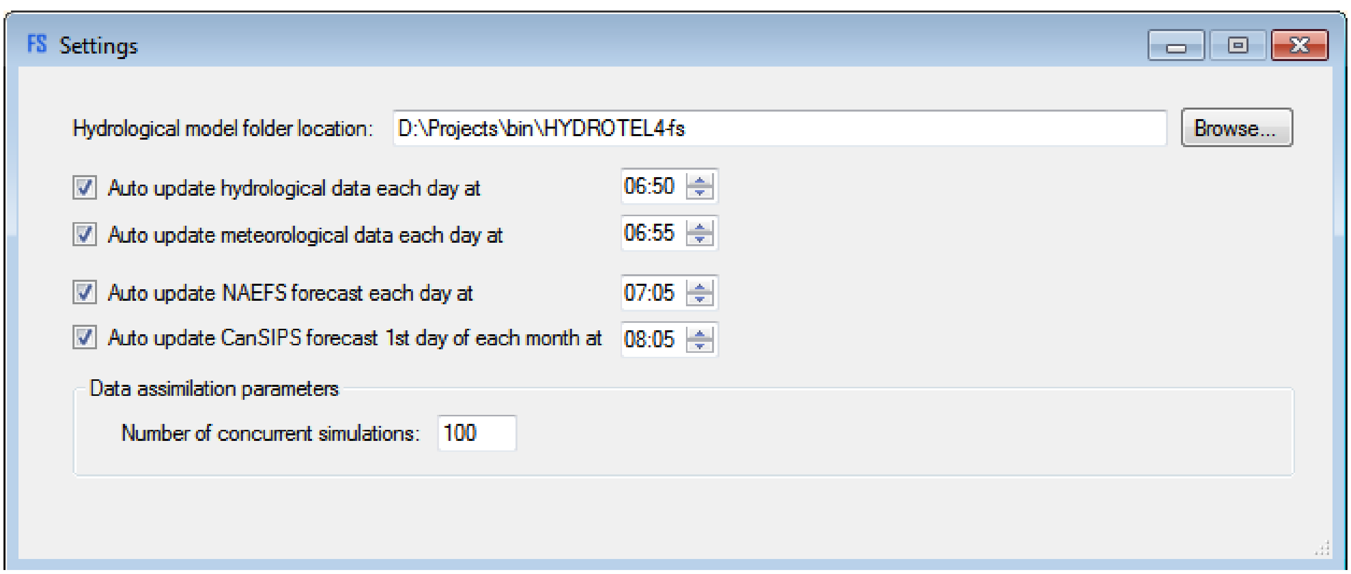


Figure 2.16 Screen capture of the Tools menu.

The Tools menu introduced in Figure 2.16 refers to a Settings menu where the user can: (i) specify the location of the HYDROTEL folder; (ii) indicate the time of the day for every Auto update (hydrological, meteorological, NAEFS, CanSIPS data); (iii) specify the number of concurrent simulations depending on the available computing resources.

3. Permafrost and multilayer snow modules

3.1. Permafrost module

3.1.1. General methodology and literature review

A warming climate can induce thawing of permafrost and activate deeper groundwater flow paths; resulting in greater base flow and affecting the overall hydrological dynamics of a watershed (Slaughter et *al.*, 1995, Kurylyk et *al.*, 2014). For example, in near-arctic landscape and ecosystem, Karlsson et *al.* (2011) illustrated how climate change leads to reduction of the permafrost areal extent, as well as significant changes. Saito et *al.* (2007) concluded that by 2100, a significant proportion of permafrost will have become a deeper and active layer, highlighting the importance of simulating the thawing process in hydrological studies. More recent articles have come to similar conclusions (*e.g.* Wellmann et *al.*, 2013, Wright et *al.*, 2009). In Wolf Creek Watershed, southeastern Yukon, where discontinuous permafrost is present, Carey et *al.* (2013) explained that a considerable part of the snowmelt discharge results from near-surface soil melt thaw. Indeed, in this watershed, Rasouli et *al.* (2014) found that permafrost degradation and ground thaw have been induced by an overall warming climate. Given the potential impacts of permafrost thaw on watershed hydrology, several authors have proposed various simulation models. Kurylyk et *al.* (2014) presented several mathematical theories and simulation tools including analytical solutions for subsurface heat transport with freezing and thawing. Riseborough *et al.* (2008) summarized recent advances in permafrost modelling while focusing on the Stefan Model, a widely used analytical equation (*e.g.*, Williams et *al.* 2015). Hayashi et *al.* (2007) introduced a simple heat transfer model to simulate thawing of the permafrost active layer and provided a methodology to integrate in a hydrological model. Their results corroborated field data from a wet, organic-covered watershed in a discontinuous permafrost region of northwestern Canada. Other models based on complete energy balance exist (*e.g.*, Lehning et *al.* 2006), but input data and intensive computational requirements are not well suited for hydrological forecasting systems relying on modest resources.

For this project, the focus is on implementing an analytical model in HYDROTEL. Using data collected in Wolf Creek Watershed, the analytical model will be compared with two frozen-soil modules already integrated in HYDROTEL, those of Rankinen et *al.* (2004) and Thorsen et *al.* (2010). With respect to operational forecasting on the studied watersheds, much of the added-value of a permafrost module will rely on a permafrost probability map of Yukon from Yukon Geomatics public portal and expert-knowledge of the active layer depth (*e.g.*, in Aishihik, thin, warm permafrost is likely present at higher elevations; whereas in Mayo permafrost is expected to be colder, deeper and with a thinner active layer). Permafrost researchers at Yukon College will provide guidance. An identification of permafrost sites by viewing aerial pictures will provide detections about phenomenon of thermokarst during the last 10-50 years. These detections will provide information about characteristic and evolution of these permafrost sites. Some basic fieldworks have been put into place in order to survey the active layer. Such field work is underway by NCE students. It is done on foot as there is decent road access and trails to higher elevations in studied watersheds.

3.2. Snow module

3.2.1. General methodology and literature review

Snow modules of hydrological models vary greatly, from simple empirical degree-day models to complete thermodynamic models, explicitly simulating energy and mass exchanges throughout the snowpack. The former models (*i.e.*, one-layer model) have proven to accurately simulate point-scale snow accumulation as well as snowmelt (*e.g.*, SRM (Martinec, 1975; Abudu et *al.*, 2012)). Meanwhile, thermodynamic snow models such as SNTHERM (Jordan, 1991), CROCUS (Brun et *al.*, 1989, 1992) or SNOWPACK (Bartelt and Lehning, 2002), to name a few, simulate snowpack stratigraphy and energy exchanges between layers of snow. Langlois et *al.* (2009) recently showed that these multiple-layer models could produce satisfying SWE estimates over boreal environments, but they require extensive meteorological data and structural information on snow cover. When simulating watershed discharge with SAC-SMA (Finnerty et *al.*, 1997, Burnash, 1995), Franz et *al*. (2008) illustrated that a more complicated model with several layers (*i.e.*, SAST (Jin et *al*, 1999a,b)) did not necessarily perform better than a simple one-layer model (SNOW17 (NWS, 2004)). Essery et *al.* (2013) carried out a comparison of several models and concluded there is no “best” model, but rather a group of model configurations that can provide consistently good results.

The snow module available in HYDROTEL is a single-layer, mixed degree-day/energy balance (DD/EB) model (Fortin et *al.*, 2001, Turcotte et *al.*, 2003, 2007) requiring air temperature and precipitation as input data. The model simulates five snowpack state variables, namely SWE, snow depth, heat deficit, liquid water content, and surface albedo. The following processes are modelled using empirical relationships: air/snow and ground/snow interface melt, compaction, albedo evolution and liquid water retained by the snow cover. Using 5-year of ground-based gamma ray monitoring and flow measurements in a boreal watershed in northern Quebec, Oreiller et *al.* (2014) compared simulations of SWE and streamflow with two contrasting approaches: the current HYDROTEL module (small number of inputs, calibration required) and CROCUS (Brun et *al*., 1989, 1992) (large number of inputs, no calibration needed). Results showed that after accounting for blowing snow sublimation and relocation based on a simple parameterisation effective after a certain wind speed threshold, CROCUS performed much better than the current DD/EB model. Streamflow simulations showed that the main peak flow could be captured when using CROCUS, but the second peak, because of delayed snowmelt from forested areas, could not be reproduced due to a lack of sub-canopy radiation data. Results also highlighted the lack of thermal inertia associated with a single-layer model. That is, for a specific spring, a sudden and unexpected loss of one third of the SWE simulated by the DD/EB model was manifestly caused by seven days of warm weather with daily maximum temperatures above 0 °C, and highs near 10 °C. CROCUS was more robust for such days. These results illustrate potential trade-offs between simple one-layer models and multiple-layer models. For northern environments such as the Yukon Territory, blowing snow and snowpack sublimation (*e.g.*, Pomeroy et *al.* 2012, MacDonald et *al.* 2009, Musselman et *al.* 2015) and other processes such as snow redistribution (*e.g.*, MacDonald et *al*. 2009) could provide additional challenges. Depending on topography, climatic conditions, wind speed and land cover, the effects of sublimation can be very different; and the different types of sublimation can be more or less important (blowing snow sublimation, drifting snow sublimation, *etc*).

For all the above reasons, the focus here is on assessing and improving the DD/EB model of HYDROTEL in Yukon and on deriving/adapting a two- or three-layer snow module accounting for snow sublimation and redistribution. The MASiN model (Mas, 2016), the MISBA model of Islam and Gan (2015) and the Distributed Snow Model (DSM) of Musselman et *al.* (2015) will provide starting inspiration with an upper snow layer and a lower snow layer interacting with the atmosphere and the soil, respectively.

For snow redistribution a topography-based concept will be explored as snow tends to accumulate first and melt last in hollows. Meanwhile, simulated SWE will be assessed using snow surveys conducted by NCE and Yukon Government and ground-based gamma ray monitoring data in the Upper Yukon River Watershed operated by YEC.

The aforementioned multi-layer snow model MASiN, recently developed by Mas (2016), uses energy balance and mass balance instead of degree/day equation and has been applied on several studies sites in Canada and Sweden. It was compared to two empirical models, those of Farbrot and Hanssen-Bauer (2009) and Baraer *et al*. (2010), and to the mixed degree-day energy balance of HYDROTEL. The results show that MASiN could, on average, achieve better performance than each of aforementioned models. In the coming year, we will further compare MASiN and the DD/EB model of HYDROTEL using data collected in northern Quebec (Oreiller *et al*., 2014) and Yukon.

4. Glacier module

4.1. General methodology and literature revue

During the course of the first year of the project, it was decided to include the Upper Yukon River Watershed into the forecasting system. Such decision requires the development and implementation of a glacier module into HYDROTEL. Glacier dynamics becomes relevant to watershed hydrology during the recession limb of the annual hydrograph as summer flows are mostly made up of precipitation runoff, subsurface runoff and glacier melting processes.

In the literature, it is found there are different types of glacier models used throughout the world. MacDougall et *al*. (2011) listed two (2) major groups of distributed empirical models commonly used to characterize the melting of glaciers. There are the temperature index models and the physically-based models derived from energy balance. The first type of models assumes a strong correlation between air temperature and melting of glaciers through an empirical degree-day coefficient. In the second type, the energy required to melt a glacier is a function of the latent heat of fusion, water density, and two empirical factors accounting for net radiation and turbulent sensible heat flow. For their study on the River Bridge Watershed in British Columbia, Stahl et *al*. (2008) used the first type of models to account for the impact of glacier melt on stream flow. The model was integrated in the semi-distributed HBV-EC model. Hock (2003) confirmed that the degree-day approach represents a simple method to effectively determine the mass balance of a glacier. Similarly, Samuel et *al*. (2016) used the empirical DETIM model in their study in the Upper Yukon Watershed. They compared mass balance provided by DETIM with those derived from satellite imagery as well as that estimated by the distributed CRHM model which has been widely used in cold regions of Canada. In addition to daily flow, Gsell (2014) used the annual glacier mass balance to validate the hydrologic model used in a mountainous watershed.

In our study, we will use methods that will allow for calibration and validation of the results of the glacier module and those of the adapted HYDROTEL model. We will use GRACE (Gravity Recovery and Climate Experiment) data and a volume-surface relationship commonly used in multiple glacier studies.

While Samuel et *al*. (2016) used a volume-surface relationship to determine the rate of change of glacier volume; Stahl et *al*. (2008) simulated the advance or withdrawal of the glaciers by using a mass balance determined through modeling. The relationship exploited in these two studies carried out in this subarctic zone, is that of Chen and Ohmura (1990). Bahr et *al*. (1997) confirmed the physical basis of this empirical relationship based on the geometry of warm glaciers throughout the world (Stahl et *al*., 2008). We will also use this relationship in order to determine glacier mass balance in the Upper Yukon River Watershed.

GRACE provides using satellite images (i.e., data) a monthly field of gravity over the world at the spatial scale of several hundreds of kilometers (Tapley et *al*., 2004). GRACE allows to have a variation of mass. Hock et *al*. (2017) sets out that GRACE has helped to revolutionize the estimation methods of the state and the change in mass of glaciers. In our study, we are using the inversion method developed by Castellazzi et *al*. (2017) during their study on groundwater in Mexico City. Farinotti et *al*. (2015) applied the method on glaciers to assess mass losses. These results are very encouraging as they provide a mean of reducing the estimation errors and pave the way to an efficient framework to estimate the monthly evolution of the glacier masses. We will use as well the data to determine a mass balance which will be compared to those obtained by modeling and those derived from the surface -volume relationship.

Through these various tools and methods, we will be able to estimate the volumes of water resulting from the melting of glaciers and contributing to the flow in Whitehorse.

5. Watershed hydrology and large-scale circulation patterns

5.1. General methodology and literature revue

In regions with snowmelt-driven runoff, spring freshet represents a major contribution to annual runoff, the possibility of oceanic-atmospheric circulation patterns inducing regime shifts could have significant implications for seasonal inflow and river forecasting. The El Niño Southern Oscillation (ENSO) index is the most dominant interannual signal of climate variability induced by such patterns; influencing precipitation, streamflow and flood-risk around the world (Ward et *al.*, 2014). For southern Yukon, the Pacific Decadal Oscillation (PDO) has a more dominating effect than ENSO (PDO response being modulated by ENSO) (Wang et *al.*, 2006). Investigating potential links between PDO and seasonal streamflow patterns in southeast Alaska, Neal et *al.* (2002) showed that annual discharge changes little; however, seasonal patterns change significantly throughout the year. There was relatively high winter flow and low summer flow during warm PDO in non-glacier-fed watersheds. Analyzing the two most recent modes of PDO in the Yukon River Watershed, Brabets and Walvoord (2009) observed that during warm PDO, there was increased winter flow, likely resulting from groundwater input enhanced by permafrost thaw. Woo and Thorne (2008) found that rivers in Alaska, Yukon, Northwest Territories, British Columbia and Alberta have variable responses to PDO signals; non-climatic factors such as location, topography and storage modifying the effects.

Using self-organized maps based on an Artificial Neural Network algorithm Cassano and Cassano (2010) found clear links between atmospheric circulation patterns and spatial distribution of summers and winter precipitation in the Yukon Territory. Kalra et *al.* (2013) applied a Support Vector Machine (SVM) technique (*i.e.*, statistical-learning model) to a snowmelt-driven watershed to forecast spring-summer flow from climate indices (PDO, ENSO, among others). Results reveal a strong association between coupled indices compared to their individual effects. Taschetto et *al.* (2014) analyzed ENSO representation in 34 CMIP5 (Coupled Model Intercomparison Project Phase 5) models produced by the Intergovernmental Panel on Climate Change (IPCC) (Taylor et *al.*, 2012) and found most of them realistically simulated observed intensity and location of maximum sea surface temperature (SST) anomalies during ENSO events. CMIP5 generation of global climate models are known to corroborate key Pacific climate mode and their teleconnections to North American climate (Polade et *al.*, 2013). Sheffield et *al.* (2013) analyzed CMIP5 historical simulations, and found that frequency and mean amplitude of ENSO were generally well reproduced, although teleconnections with North American climate widely varied among models. Fuentes-Franco et *al.* (2015) analyzed ENSO and PDO in CMIP5 simulations and found the models reproduced well the constructive interference between these oscillations patterns when compared to observations (*i.e.*, positive ENSO and PDO or negative ENSO and PDO). The destructive interference was less accurately reproduced. For the 2nd half of the 21st century, overall strengthening of both ENSO and PDO signals could be found.

For this project, we are using climate models to highlight the structure of teleconnections between Pacific climate variability and the regional hydroclimate of the Yukon Territory delineated by a buffer region including parts of Alaska, British-Columbia, Alberta and Northwest Territories. Our partner NCE uses statistical/machine-learning/data-driven models to highlight the strength and significance of long-term linkages between large-scale climate oscillations and climate. NCE integrates the developed equation in their data assimilation procedure, while the focus of the current work package is to investigate, using CMIP5 outputs, whether or not these linkages will remain under changing climate conditions.

Using the methodology developed by Polade et *al.* (2013), monthly Pacific SST and precipitation over the region of interest is being analyzed and compared with observations over extended past (*e.g.*, 1901-1999) and future (*e.g.*, 2000-2100) periods. Results of the study conducted by Polade et *al.* (2013) serve as a first screening of potential climate models for this teleconnection assessment of hydroclimate variables (*i.e*., precipitation (P), temperature (T)) and large-scale circulation patterns. Simulated SSTs and concurrent precipitation and temperature will come from either CMIP5 or CORDEX datasets made available to this project by the Ouranos consortium. Monthly observed PT will come from observed meteorological conditions, or reanalyses (*e.g.*, CFSR (Saha et *al.*, 2010), ERA-Interim (Dee et *al.*, 2011), MERRA2 (Rienecker et *al.*, 2011), JRA55 (Kobayashi et *al*., 2015), 20CR (Compo et *al*., 2011) or ERA-20C (Poli et *al*., 2013)), while monthly average observed SSTs will come from the Extended Reconstructed SST v3b (Smith et *al.*, 2008). The different datasets will be compared to each other on the studied region to assess their quality.

Regarding the teleconnections, the analysis will be first restricted to the months of January-February-March, the season of strongest teleconnections, but could be extended to other months. Teleconnections will be first assessed by computing or downloading time series of indices (PDO, SOI, AO) that will be linked to PT time series. Teleconnections will then be assessed using spatial patterns of SST through different techniques such as singular value decomposition (SVD) of the cross-variance matrix between detrended SSTs over the Pacific Ocean (north of 30°S) and PT over the region of interest. Other large-scale variables could be considered such as SLP. Data pre-processing include removing any trend from all individual grid point time series. Focus will be primarily applied on the first mode that captures the ENSO-PDO pattern and much of the teleconnection to precipitation. The second SVD considered should identify an ENSO-PDO spatial pattern. Depending on results of the statistical analysis conducted by NCE, the Pacific North American pattern, the North Pacific index, the North Atlantic Oscillation, and the Arctic Oscillation could be considered, but the emphasis will primarily be on ENSO and PDO. Bonsal et *al*. (2006) used the same indices to examine the impacts of various climate oscillations on Canadian river-ice durations. For the Yukon River basin, teleconnections between SSTs and observed stream flows will also be investigated.

The established teleconnections could be incorporated in the ensemble forecast framework. Indeed, large-scale circulation patterns could be used to select precipitation and temperature conditions similar to the ones of the current situation. It would then be possible to construct a range of plausible future meteorological conditions from what already happened in the past.

6. Hydroclimatic assessment

6.1. General methodology and literature revue

Hydroclimatic assessment will be performed using downscaled daily Canada-wide climate scenarios from the latest CMIP5 climate simulations (Taylor et *al.*, 2012) offered by the Pacific Climate Impacts Consortium (PCIC). Two scenarios of Representative Concentration Pathways (RCPs), namely RCP4.5 and RCP8.5, are being considered; the former being viewed as optimistic, while the latter deemed pessimistic (Van Vuuren et *al.*, 2011). Combinations of climate models and RCPs where selected and made available to this project by the Ouranos consortium. The horizon of interest is 2040-2070; the 1970-2000 representing the reference horizon. The number of climate simulations available is 33. To provide a consistent picture of potential impacts of climate change on future inflows at the Mayo and Aishihik Hydroelectric Facilities, HYDROTEL will be used as the basic hydrologic model. The emphasis is on identifying long-term trends in flow volume, flow timing and extreme events. The pre-identified hydrological indicators will be related to spring high flow and volume, summer and fall high flow, winter low flow, summer low flow, and mean flow regime (e.g., annual maximum daily peak flow and 14 day spring flow with 2- and 20-year return periods). A non-stationary frequency analysis will be used to assess the return period (Rousseau et *al.*, 2014). The change signal analysis procedure developed by MDDELCC (2015) will be used to report a distribution of change of any given set of hydrological projections (*i.e.*, combination of one climate simulation and HYDROTEL). Direction (increase or decrease) and magnitude of change (*i.e.*, median value of the set of change values) along with dispersion of signal around the magnitude (half of the probable values around the median value) will represent the basic descriptors of change of the hydrological indicators of interest. The terminology characterizing the direction of change will be based on classes of hydrological projections (*e.g.*, highly probable, probable, status quo) and a confidence level will be provided (*e.g.*, high, moderate, limited). The latter will rely on the capacity of the hydroclimatic models to simulate observed flows.

7. Project schedule

At this point, the project is proceeding as planned; with some work packages (WPs) ahead of schedule, while others had a late start, but not to the point of slowing down the project at all. Table 7.1 introduces the project schedule which was updated after it was decided a few months after the beginning of the project to substitute the reservoir management work package (old WP3) for the hydrological modelling of the Upper Yukon River Watershed (new WP3) and subsequent integration in the forecasting system. The following paragraphs summarize the December 2017 state of each WP described in the previous chapters of this report with respect to the project schedule introduced in Table 7.1.

WP1 – Forecasting System

In December 2017, INRS will complete the implementation of the forecasting system on the modelling server at YEC in Whitehorse (WP1), thanks to IT staff for their collaboration. The system will be operational for Aishihik and Mayo - this actually is one year ahead of schedule with respect to Mayo - including implementation of the Ensemble Kalman Filter (EnKF) DA developed by NCE (see ARD progress report produced by NCE). The DA was integrated in the forecasting system in October 2017. As far as DA goes, the forecasting system is almost two years ahead of schedule, which is remarkable. For the Upper Yukon River, NCE must develop the DA scheme for short lead time (NAEFS). Meanwhile INRS will integrate a glacier module into HYDROTEL (new WP3) and then NCE will develop the DA for seasonal and annual lead times (CanSIPS). In early January 2018, INRS will provide training to YEC staff on how to operate the system.

WP2 – Permafrost and Snow

The development and validation of the permafrost and multilayer snow modules are the thesis subjects of an INRS Ph.D. student who started in September 2017. The work is in the preliminary stage of implementing the methodology introduced in Chapter 3; that is selection and testing of a double-layer snow model and at the beginning of identifying permafrost sites based on available data collected by NCE. The integration of the modules in HYDROTEL will be performed in the third year of the project.

Table 7.1 Project schedule

	2016-17		2017-18				2018-19				2018-19	
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
WP1 - Forecasting system (FS)												
1st version of the FS												
Construction of databases												
Model calibration												
Implementaiton of the F procedure												
Development of the GUI												
Implementation at YEC (training)												
Final version of FS												
Updating w/r to WP2												
Updating w/r WP3												
Integration of the ARD DA techniques												
WP2 - Permafrost & snow												
Permafrost module												
Integration of an analytical model												
Permafrost surveying												
Validation of the model												
Multilayer snow module												
Development of the model												
Validation of the model												
Snow surveying												
WP3 - Glacier												
Hydrological forecasting model												
Climate change simulation model												
Validation of the models												
Integration off-line in the F procedure												
WP4 - O-A circulation & hydrology												
Selection of CMIP5 simulations												
Data preprocessing												
Construction of observed databases												
Development of computational procedure												
Identification of large-scale circulations												
Large-scale circulations & hydrology												
WP5 - Hydroclimatic assessment												
Selection of CMIP5 simulations												
Simulations												
Frequency analysis												
Change signal analysis												
Meetings/activities												
Outreach												
Technical												
Technology transfer												

Simulated SWE will be assessed using historical snow surveys conducted by NCE and Yukon Government, and ground-based gamma ray monitoring in the Upper Yukon River operated by YEC. Supplemental snow surveys on foot are done during winter/spring in Aishihik and Mayo by NCE. A snow temperature profile sensor will be installed in Aishihik by NCE as soon possible. The data will be used by INRS to validate the modelling of SWE. Despite a late start due to administrative constraints related to the issuing of a student visa - the PhD student actually arrived at INRS in September instead of June - this WP is on target.

WP3 – Glacier

This WP focuses on the development and integration of a glacier module in HYDROTEL in order to explicitly account for the presence of glaciers in the Upper Yukon River Watershed. It is the thesis subject of an INRS PhD student. As reported in Chapter 4, this item is well underway and proceeding according to the updated project schedule. This is quite remarkable given the fact that the PhD student started in September due administrative constraints related to a student visa that took more time than expected to be issued.

WP4 – Ocean and atmosphere circulation and hydrology

This item is ahead of schedule as it was originally planned to start in January 2018. Indeed, it started in September 2017, thanks to the successful recruitment of the postdoctoral fellow who accepted to start early her internship at INRS.

WP5 – Hydroclimatic Assessment

This item will start in the coming year, although we have already received the CMIP5 simulations from Ouranos.

Meetings and Activities

During the first year of the project, regular conference calls, involving project managers at INRS, YEC and NCE, were held to insure the project was on track.

INRS team members travelled twice to Whitehorse for technical meetings (March and July) and a NCE member travelled once to Quebec City to coordinate the integration of the DA in the forecasting system. The planned December visit to Whitehorse was postponed to January due to outstanding airfares. The January 2018 trip will involve technical and technology transfer meetings between INRS, YEC and NCE.

Finally, the INRS-NCE team shared preliminary findings of the project with the scientific community via a poster presentation at the Ouranos Symposium held in Montreal in November (Rousseau et al., 2017a) and two oral presentations at the Arctic Change 2017 conference held in Québec City in December (Rousseau et al., 2017b; Samuel et al., 2017).

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