Daily streamflow and water temperature simulation: case study of Pacific Coast (Canada)

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ABSTRACT

The Pacific coast is considered one of the most vulnerable areas in Canada to oil spills, both at the environmental and socioeconomic levels. To forecast fate and transport of oil in the waters off BC’s central and north coast, the Department of Fisheries and Oceans Canada (DFO) is implementing a coastal ocean model (FVCOM: Finite Volume Coastal Ocean Model) that requires freshwater boundary conditions as inputs. One of Environment and Climate Change Canada's (ECCC) contributions is to provide realistic daily simulations of river flows with corresponding stream temperatures. The objective of this study is to present and discuss results of streamflow and temperature simulations based on a cascade of numerical models (the ISBA land-surface scheme, the WATROUTE river routing model and the RBM river temperature model) forced offline by the GEM atmospheric model, for various simulation periods between 2013 and 2015. Over this time period, GEM outputs were available from three configurations: RDPS (10-km resolution over North America for the whole period), LAM-WEST (2.5-km resolution over southern BC and Alberta until November 2014), HRDPS (2.5-km resolution, national coverage since October 2014). The impact of using a gridded snow depth analysis in order to constrain the land-surface model was also evaluated. The performance of ISBA-WATROUTE-RBM was compared to observed daily streamflow and water temperature at three streamflow gauging stations. Overall, more accurate estimates were obtained when using the higher resolution HRDPS configuration of GEM, and using the snow analysis to constrain the surface model. The modelling approach also has potential to be used for water resources managers in need of forecasted streamflow and water temperature for management decisions in the face, for example, of thermal pollution (anthropogenic effects) and climate change impacts for small river basins.

1. INTRODUCTION

Canada is the world’s largest coastal nation with 244 000 km of coastline under its jurisdiction. It is surrounded by three oceans, including a sea of arctic ice that support some of the most abundant and diverse webs of marine life on Earth. Most of the world's creatures live in the ocean. More than half of the Earth's oxygen is produced there. For upholding marine safety, Canada has a comprehensive, multi-layered regime that includes legislative and regulatory frameworks, standards and policies, harmonized with international standards. In recent decades, oil has been safely transported in Canadian waters, without major incident. However, the coast of southern British Columbia (BC) is considered one of the most vulnerable areas in Canada to oil spills, both at the environmental and socioeconomic levels (St. Lawrence Coalition, 2014). Reviewing the magnitude of present operations and potential increases in tanker traffic associated with the proposed Northern Gateway pipeline in Canada’s west coast, it is necessary to understand the risks posed by this pipeline in order to protect communities and environment from harmful effects of oil spill. As stated in a report published by BC Ministry of Environment (2013): "it is important to acknowledge that: (1) spills can still happen even with the best possible prevention and safety measures in place, and (2) even the best possible spill response system cannot guarantee that resources at risk will be protected from negative impacts if a spill occurs". Although this is certainly true, impacts of oil spills can potentially be reduced if the response to an event makes optimal use of accurate forecasts from an integrated environmental prediction systems that simulates the behaviour of oil patches in response to atmospheric and oceanic conditions.

1.1 Project scope

Driven by federal mandates, the west coast of Canada currently benefits from several marine oil spill prevention, preparedness, and response-related initiatives. Indeed, under the World Class Oil Spill Response Regime (WCOSRR), the Department of Fisheries and Oceans Canada (DFO) is implementing a coastal ocean model to forecast fate and transport of oil in the waters off BC’s central and north coast. One of Environment and Climate Change Canada's (ECCC) contributions is to provide a short-term forecast model of river flows with corresponding stream temperatures (landward boundary conditions for Finite Volume Coastal Ocean Model (FVCOM)). To this end a cascade of environmental models will be used (Figure 1):

- the Global Environmental Multiscale Model (GEM);
- the GEM-Surf land-surface prediction system, also known as the Surface Prediction System (SPS);
- the streamflow routing model (WATROUTE);
- the stream temperature model RBM (River Basin Model).

Although this cascade of models is set up and tested in watersheds which flow into Hecate Strait (BC), the models are relocatable to other watersheds and the data used to drive them is available for all Canadian provinces.

1.2 Project objectives

The objective of the project is to present how the GEM, GEM-Surf, WATROUTE and RBM models were set up and coupled over the watersheds flowing into Hecate Strait and discuss preliminary results obtained for the period of October 2013– July 2015. The performance of WATROUTE-RBM will be evaluated using observed daily streamflow and water temperature dataset at three gauging stations from three WCOSRR subdomains that they are parts of the watersheds that drain directly into Douglas Channel and Hecate Strait. Two resolutions will be considered for GEM: 10-km and 2.5-km, in order to assess whether increasing the spatial resolution improves the performance of WATROUTE and RBM for these watersheds of the Pacific coast. The impact of using a snow depth analysis to control GEM-Surf model drift will also be evaluated. Along with preliminary results from this modeling system, recommendations for improving the physical process representation in the various models employed will also be presented.

The report is organized as follows. Section 2 presents the methodology, study area and characteristics of the datasets that are used for implementing and evaluating the models. The preliminary results of the streamflow and water temperature simulations against observed data are presented in Section 3, and the discussion and conclusion are presented in Section 4.

2. METHODOLOGY

2.1 Description and application of numerical models

The thermal regime of rivers is influenced by many factors such as atmospheric conditions, topography, riparian vegetation, stream discharge, and heat fluxes (e.g. Poole and Berman 2001; Caissie et al. 2007; Webb et al. 2008). Since these impacts could occur at small time and length scales, analytical tools that consider, for example, the influence of the hydrologic regime (e.g., stream flow), are required. In order to simulate stream flow, it is required (1) to obtain atmospheric forcing data, (2) to simulate land-surface processes – including runoff – and (3) to route this runoff to the outlet of the watershed. Figure 1 illustrates the modelling strategy that is used in the present study. Starting from atmospheric forcing data provided by the GEM atmospheric model, streamflow is simulated using the GEM-Hydro platform, which combines a land-surface prediction system (GEM-Surf) with a routing model (WATROUTE). GEM-Surf offers two options for simulating land-surface processes: the ISBA and the SVS land-surface models. Outputs from GEM, GEM-Surf and WATROUTE are provided to RBM which then simulates river temperature based on these inputs (Yearsley, 2009). Stream flow and temperature at the mouth of each river can then be provided to ocean models such as FVCOM as boundary conditions. More details are given below for each model.

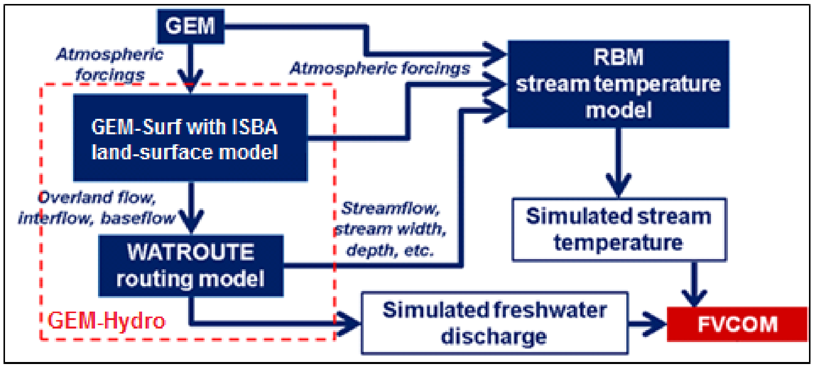

Figure 1. Flowchart of the hydrological and water temperature modelling framework presenting the links between the streamflow routing model (WATROUTE) and the process-based water temperature model (RBM) used to assess water temperatures (boundary conditions), and model input and output.

GEM atmospheric model

The Global Environmental Multiscale (GEM) model is the only atmospheric model used by ECCC for numerical weather prediction purposes. It represents atmospheric processes on a grid, but it also represents surface processes using a tiling approach. The surface of each grid cell is subdivided into a vegetated tile, a glacier tile, an open water tile, an ice-covered water tile and an urban tile. GEM configurations are available to use at various resolution, from 200 m to 200 km, depending on the application. For the vegetated tile, all current configurations of GEM rely on the ISBA land-surface model to represent the interactions between the surface, the biosphere and the astmosphere.

For this project, three configurations of GEM will be used: RDPS, LAM-WEST and HRDPS. The RDPS (Regional Deterministic Prediction System) is an operational configuration of GEM that provides 48-h weather forecasts over North America on a 10-km grid that are updated every 6-h. The LAM-WEST is a configuration of GEM that provided 24-h weather forecasts over Southern British Columbia and Alberta on a 2.5-km grid once per day. It was decommissioned in November 2014 and replaced by the HRDPS (High-Resolution Deterministic Prediction System) configuration of GEM, which provides 48-h weather forecasts over most of Canada (except the arctic islands) on a 2.5-km grid. Like the RDPS, these forecasts are updated four times per day.

GEM-Surf, also known as the Surface Prediction System (SPS)

GEM-Surf, also known as the Surface Prediction System (SPS) is a configuration of GEM that is used to only run the surface model of GEM, without running the atmospheric model. It requires inputs that can be provided by a previous GEM run, such as precipitation, temperature, humidity, wind, pressure, and incoming radiation. GEM-Surf can be used to assess the anticipated impact of changes to the surface of GEM without having to run the atmospheric model itself. This can drastically reduce computing time compared to a run where the atmosphere interacts with the surface.

In this project, GEM-Surf is used to generate the daily surface data sets required by WATROUTE and RBM using the three configurations of GEM presented in the previous section (RDPS, LAM-WEST and HRDPS). GEM-Surf is computationally inexpensive (compared to GEM), and therefore suitable for downscaling GEM surface fields over very high resolution grids (e.g., Carrera et al., 2010), or for testing new land-surface models. There are two main reasons for using it in this study (rather than relying directly on GEM outputs): firstly, outputs from GEM required by WATROUTE and RBM were not all kept in the GEM archive; secondly, GEM relies on a rather crude surface data assimilation system to obtain initial conditions of soil moisture, soil temperature and snow pack properties. For hydrological applications, better results are generally obtained (especially for groundwater recharge) by running the land-surface model GEM-Surf offline, from archived GEM outputs, because the online data assimilation process tends to perturb significantly the modelled soil moisture content in order to improve the simulation of air temperature and humidity near the surface.

When running GEM-Surf in order to provide boundary conditions to the WATROUTE routing model over land areas, a land surface scheme (LSS) is needed. The LSS used in the present study is the Interactions between the Soil, Biosphere and Atmosphere (ISBA) (Belair, 2003). ISBA is currently used operationally in CMC’s local, regional, and global forecasting systems. The basic function of the land surface scheme is to integrate the energy and water balances of the land surface forward in time from an initial starting point, making use of atmospheric forcing data to drive the simulation. LSS requires updates of atmospheric forcing at regular intervals. Hourly atmospheric forcing are derived from GEM for use in WATROUTE for streamflow simulation.

WATROUTE

WATROUTE uses routing algorithms of the WATFLOOD distributed hydrological model (Kouwen et al., 1993). The routing scheme solves the water balance equation at each grid-cell, and relates the water storage to outflow from the grid-cell, using Manning’s equation. WATROUTE is capable to take as input gridded values of surface runoff, interflow and baseflow output by an LSS (in this case, ISBA) for each land surface and produce a routed streamflow at any point using the finer scale river network system. Flow directions required by the routing scheme were derived from the HydroSHEDS database (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales) (Lehner et al., 2006), available at 30-second resolution on a latitude–longitude grid. The advantage of WATROUTE is the ability to view model output for any part of the watershed. Table A.1 displays the procedure needed to setup a new experiment of WATROUTE executable, while Table A.2 contains a brief overview of the files that are required as inputs and the most important output file in the root directory of the "experiment" file. After this is done, streamflow simulation results are processed and transferred to the RBM model, which will compute (per grid cell) the water temperature in the network of streams for the duration of the simulation.

RBM stream water temperature

RBM is a deterministic (physically based) one-dimensional stream temperature model that solves the 1D-heat advection equation using the semi-Lagrangian (mixed Eulerian-Langrangian) approach (Yearsley, 2009, 2012). RBM was developed for subbasins of the Columbia River and has been applied by Yearsley (2012) to the Salmon subbasin (36325 km^2) on a 1/16° spatial resolution. Water temperature is calculated for a specific stream segment based on the upstream water temperature and inflow into the stream segment, the dominant heat exchange at the air–water surface, and the inflow and temperature of water advected from tributaries and, optionally, from subsurface (van Vliet, 2015). Solutions are obtained by tracking individual water parcels along their flow characteristics and storing the output at discrete points on a fixed grid (van Vliet, 2013). The concept of the RBM water temperature model is shown in Figure 2.

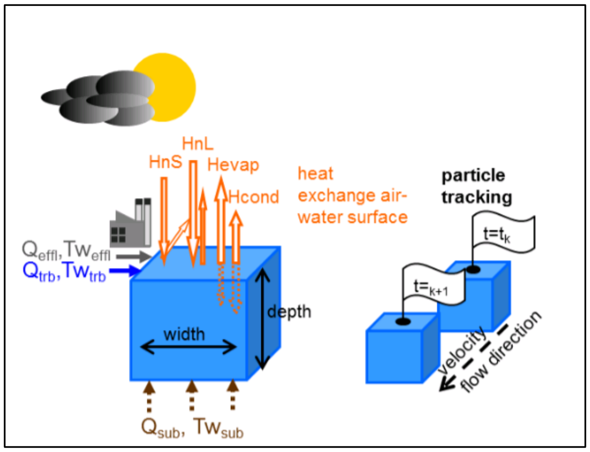

Figure 2. Concept of RBM stream temperature model. Abbreviations are used for water temperature (Tw) and flow (Q) of tributaries (trb), subsurface (sub) and thermal effluents (effl), net shortwave solar radiation (HnS), net longwave atmospheric radiation (HnL), evaporative/latent heat flux (Hevap) and conductive/sensible heat flux (Hcond). (van Vliet, 2012)

RBM assumes discharge in each river segment on each day is transmitted downstream instantaneously. To estimate water temperature at air-water interface, RBM uses an equation of Mohseni et al. (1998) nonlinear stream temperature regression model based on air temperature. The Mohseni et al. (1998) approach describes the S-curve relationship between weekly water temperature and weekly air temperature according to:

$$T_W = \mu + \frac{\alpha - \mu}{\left(1 + e^{\gamma(\beta - T_{air})}\right)} \qquad [1]$$

With $\gamma = \frac{4tan\theta}{\alpha - \mu}$

Where μ= lower bound of water temperature (°C); α =upper bound of water temperature (°C); γ= measure of the slope at inflection point (steepest slope) of the S-shaped relation (°C^{-1}); β= air temperature at inflection point (°C); T_w = water temperature (°C); T_{air} = air temperature (°C); *tan* θ = slope at inflection point (–). In the present study, the optimal four parameters are obtained by giving the best fit between the observed and simulated water temperature. As indicated in Figure 3, RBM model's input files can be separated into three components: (1) river geometry, (2) boundary conditions, and (3) meteorological data.

2.2 Study subdomains and data characteristics

WCOSRR domain is split into six sub-domains which are determined on the basis of ease of generating the geophysical fields required by the WATROUTE model: Kitimat, Skeena, Portland, Bentinck, Rivers Inlet and Haida (Figure 3A). Since the DFO coastal ocean model's spatial domain requires, among others, freshwater boundary conditions from Haida Gwaii to the mainland, the purpose of the present study is to provide preliminary results of the freshwater flux and temperature simulations from Kitimat, Skeena, Bentinck and Haida as they are parts of the watersheds that drain directly into Douglas Channel and Hecate Strait (Figure 4). Hourly streamflow data from regional gauge observations are widely available in the Pacific coast, while observations for stream temperature are comparatively sparse. Regional gauges having both streamflow and temperature observations were prioritized for model validation. In order to establish the validity of the WATROUTE and RBM models. The streamflow and temperature simulations were compared with available independent historical observations from three gauges: Kitimat (08FF001), Bentinck (08FB006) and Skeena River above Babine (08EB005).

Comment [VF1]: Where did this name come from? According to the Water Survey web site, the station 08FB006 is named ATNARKO RIVER NEAR THE MOUTH and is located

The observed data dataset were extracted from WSC (Water Survey of Canada; http://www.wateroffice.ec.gc.ca/index_e.html). The location of the gauging stations considered in the study is shown in Figure 3B. The characteristics of the three WSC gauge stations are briefly described in Table 1.

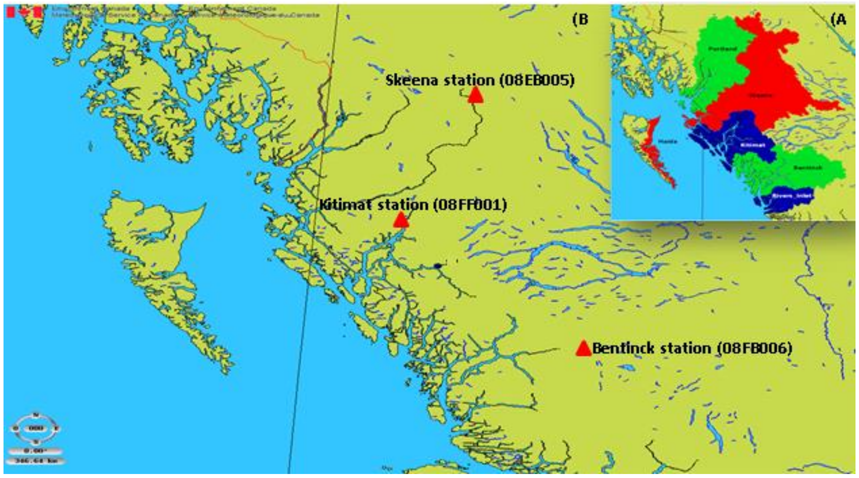

Figure 3. (A) WCTSS domain with its 6 subdomains (watersheds). Right: Hecate Strait and Douglas Chanel, (B) location of hydrological gauging stations used in the validation of WATROUTE and RBM simulation of streamflow and water temperature.

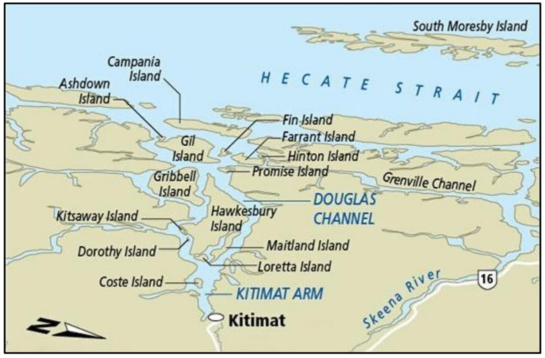

Figure 4. Location of Douglas Channel and Hecate Strait
source: http://www.bears-and-more.de/kurzmeldungen/2012-09-05.html

Table 1. Hydrometric data characteristics used in the present study

Subdomain	Drainage area (km^2)	Gauge name/ID	Description	Latitude Longitude	% glaciated	Hydrologic regime	Stream temperature

Kitimat	1990	Kitimat River below Hirsch Creek (08FF001)	Kitimat and Kemano Rivers,and other areas draining into Douglas Channel, Gardner Canal, etc.	54 03 34 N 128 40 29 W	4.5	Nivo-pluvial	Probe Real-time since Oct. 23, 2013
Bentinck	2550	Atnarko River near the mouth (08FB006)	Bella Coola River, Dean River, and other areas draining into Dean Channel, North and South Bentinck Arms	52 21 39 N 126 00 19 W	0.7	Nival	Probe Real-time since Nov 21, 2014
SkeenaAbBabine	12400	Skeena River above Babine River (08EB005)	Skeena River above Babine River	55 42 58 N 127 41 05 W	n/a	Nival	Spot (since 2008)

To quantify the performance of WATROUTE and RBM for daily streamflow and water temperature simulations, we used the mean absolute error (MAE) and mean bias (BIAS). In addition, the coefficient of determination (R^2) was calculated to quantify how strong of a linear relationship there is between simulations and observations values. The equations for the selected performance coefficients are:

$$MAE = \frac{1}{N}\sum_{t=1}^{N}|S_t - O_t| \qquad [2]$$

$$BIAS = \frac{1}{N}\sum_{t=1}^{N}(S_t - O_t) \qquad [3]$$

$$R^2 = 1 - \frac{\sum_{t=1}^{N}(S_t - O_t)^2}{\sum_{t=1}^{N}(O_t - \bar{O})^2}, \text{ with } \bar{S} = \sum_{t=1}^{N} S_t\, , \bar{O} = \sum_{t=1}^{N} O_t \qquad [4]$$

where, S_t and O_t are the simulated and observed values for time t, respectively, and N is the number of data points.

2.3 Set-up of the numerical experiments

In order to identify the best method to obtain simulations of daily streamflow and water temperature for the Kitimat domain, three different configurations of the GEM atmospheric model were evaluated: the Regional Deterministic Prediction System (RDPS), which has a 10-km horizontal resolution, the High Resolution Deterministic Prediction System (HRDPS), which has a 2.5-km horizontal resolution, and the LAM-west prediction system, which also has a 2.5-km horizontal resolution. The LAM-west system, which produced 24-h forecasts for Southern British Columbia and Alberta, was replaced in November 2014 by the HRDPS, which has the same resolution but offers Canada-wide coverage.

Both HRDPS and RDPS forecasts are issued four times per day for 48-h into the future, whereas the LAM-west forecasts were only issued two times per day. As with all atmospheric forecasting systems, skill decreases with lead time. In order to obtain continuous atmospheric forcing for land-surface simulation purposes, it is therefore best to use short-term forecasts. However, atmospheric numerical models also require some spin-up time in order to properly represent atmospheric processes. Past experience with the GEM model suggests a 6-h spin-up time. When using outputs from systems updated twice per day (RDPS and HRDPS), we therefore rely on atmospheric forecasts having lead times of 6-h to 12-h. For the LAM-west system, whose forecasts are only issued twice daily, lead times of 6-h to 18-h are used.

All of the systems considered rely on the ISBA land-surface scheme to represent surface processes, including snow accumulation and melt as well as runoff production. ISBA can be run in open-loop mode from past GEM forecasts using the GEM-Surf system. This system can also ingest a snow depth analysis in order to improve snow accumulation and melt short-term forecasts. Snow depth analyses are available on a daily basis from CMC on either a 2.5-km or a 10-km grid. The idea behind the introduction of snow analysis is to limit the risk of model drift in an open-loop simulation by bringing back the snow depth state variable of ISBA to values closer to observations. The impact of using the snow analysis in GEM-Surf was tested for the LAM-west GEM configuration only, and only for the first year of simulation.

Two water years of data were available for model evaluation: 2014 and 2015. The first year was used to identify the most promising model configuration in terms of horizontal resolution (10-km vs 2.5-km) and with respect to the use of a snow analysis to correct the snow depth simulations. The second year was kept as a verification period for this model configuration. Table 2 summarizes the various simulation approaches used in the presend study.

Table 2. Simulation approaches used in the present study and corresponding period of analysis

	Location	**Atmospheric model**	**Lead time**	**Snow analysis**	**Period of analysis**
Validation	Kitimat station (08FF001)	RDPS 10 km	6h-12h	YES	Oct. 2013-Oct.2014
		LAM-WEST 2.5 km	6h-18h	YES	Oct. 2013-Oct.2014
		LAM-WEST 2.5 km	6h-18h	NO	Oct. 2013-Oct.2014

		HRDPS 2.5 km	6h-12h	YES	Oct. 2014-Jul.2015
	Bentinck station (08FB006)	HRDPS 2.5 km	6h-12h	YES	Feb.2015-Jul.2015
	Skeena River above Babine River (08EB005)	HRDPS 2.5 km	6h-12h	YES	Feb.2015-Jul.2015
Simulation	For whole Kitimat subdomain	HRDPS 2.5 km	6h-12h	-	Oct. 2013

WATROUTE requires topographic parameters to be input into the model. Among others, the drainage area estimate for each grid is required in order to match the drainage area of the grid to what is physically observed on the land surface. The dominant drainage direction is used in determining the runoff volumes and the grid segment routing path. Figure 5 shows the flow directions (30s resolution) (or the major drainage channels) for each gauging stations.

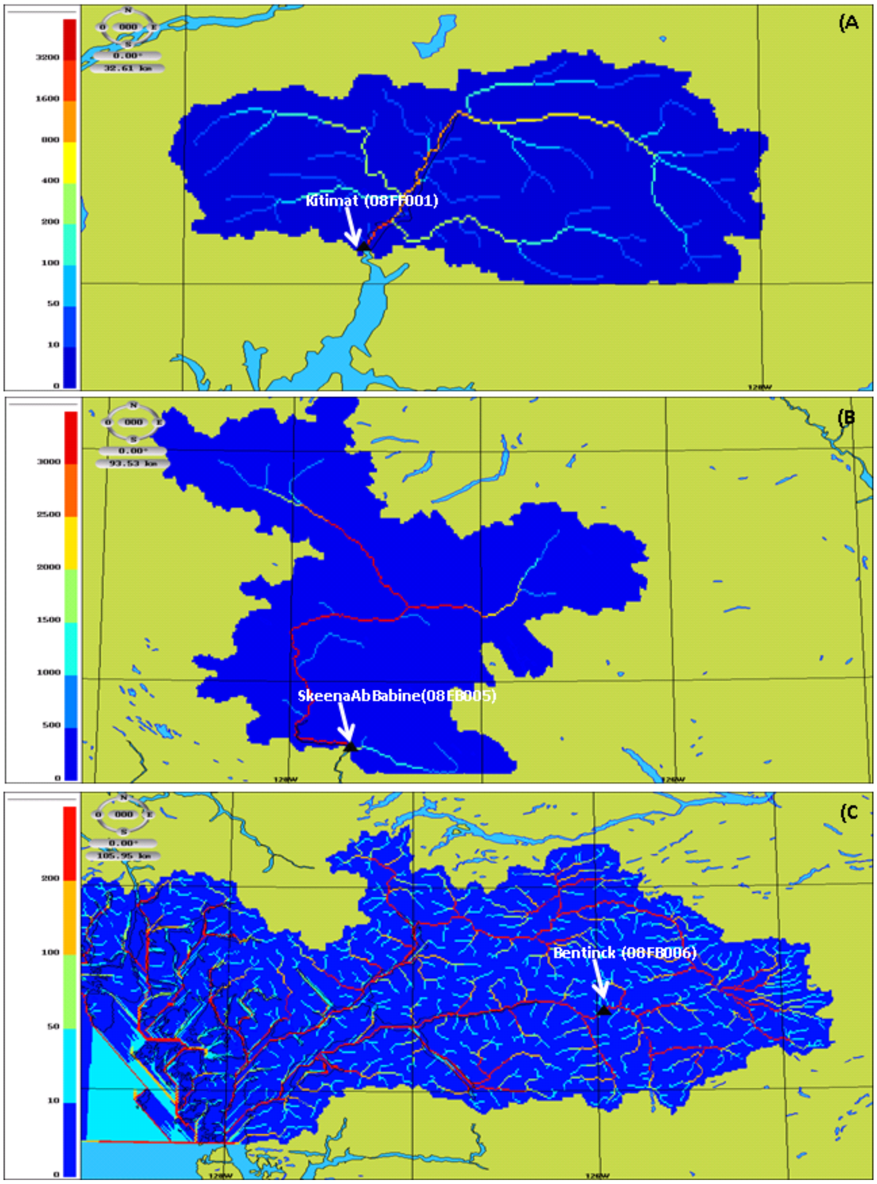

Figure 5. Watershed directions used to model streamflow at the three gauging stations (triangles): (A) Kitimat, (B) Skeena and (C) Bentinck

3. PRELIMINARY RESULTS

3.1 Performance of daily streamflow simulations

Comparing the output data of WATROUTE to the observed data is essential to determine how well the model predicts the streamflow. In the validation plots, the following can be noted. For the Kitimat station (Figure 6), the daily simulated river streamflow (cyan line) generally show a close correspondence with the daily observed streamflow (black line). Part of the river discharge overestimation for LAM-west without snow analysis can be explained by the behaviour of the snow accumulation and melt model of ISBA (Figure 6 A, B1). Indeed, the inclusion of the snow analysis in LAM-west resulted in a distinct improvement in the simulated streamflow (Figure 6B1), which is reflected by a lower value of mean BIAS and MAE (13 and 54 m^3/s, respectively) compared to the simulation without the snow analysis (111 and 118 m^3/s, respectively). This suggests that the snow analysis is useful in bringing back to reality the snow depth state variable of ISBA. Although the onset of the discharge peak in spring is somewhat too early, e.g. at Kitimat with LAM-west without snow analysis (Figure 6A), the hydrologic regime is represented more realistically when the snow analysis is included. This indicates that the inclusion of a snow analysis in the simulation process is beneficial for predicting daily streamflow in Kitimat sub-basin, and highlights possible limitations of the ISBA snow model or of the GEM forcing (and in particular solid precipitation). Compared to LAM-west predictions at 2.5-km, RDPS predictions display a large negative BIAS (-40 m^3/s vs 13 m^3/s). RDPS predictions are however slightly more accurate in terms of MAE (48 m^3/s vs 54 m^3/s). Based on a trade-off between minimum MAE and minimum bias values, the LAM-West GEM configuration with simulations updated using a daily snow analysis was selected as the most promising model configuration for this project.

Recall that the LAM-west GEM configuration was replaced by the HRDPS configuration in the fall of 2014. GEM HRDPS has the same horizontal resolution at LAM-west but better spatial coverage. The HRDPS configuration was therefore used for the second water year, and evaluated at the Kitimat station but also at the SkeenaAbBabine and the Bentinck gauging stations (Figure 7). In terms of BIAS and MAE, performance for the Kitimat station was slightly worse with HRDPS forcing over that second year than with LAM-west forcing over the first year, but remained very good in terms of correlation ($R^2 = 0.7$). At SkeenaAbBabine station, daily variability in streamflow was slightly overestimated (Figure 7A), but in general a realistic representation was found (BIAS = 89.1 m^3/s; $R^2 = 0.9$). Compared to Kitimat and

SkeenaAbBabine stations, the inclusion of snow analysis in HRDPS, at Bentinck station, did not provide good simulations of measured values (BIAS=-31.1 m^3/s; MAE=39 m^3/s); however it was suitable to capture some of the seasonal variation of streamflow (Figure 7B).

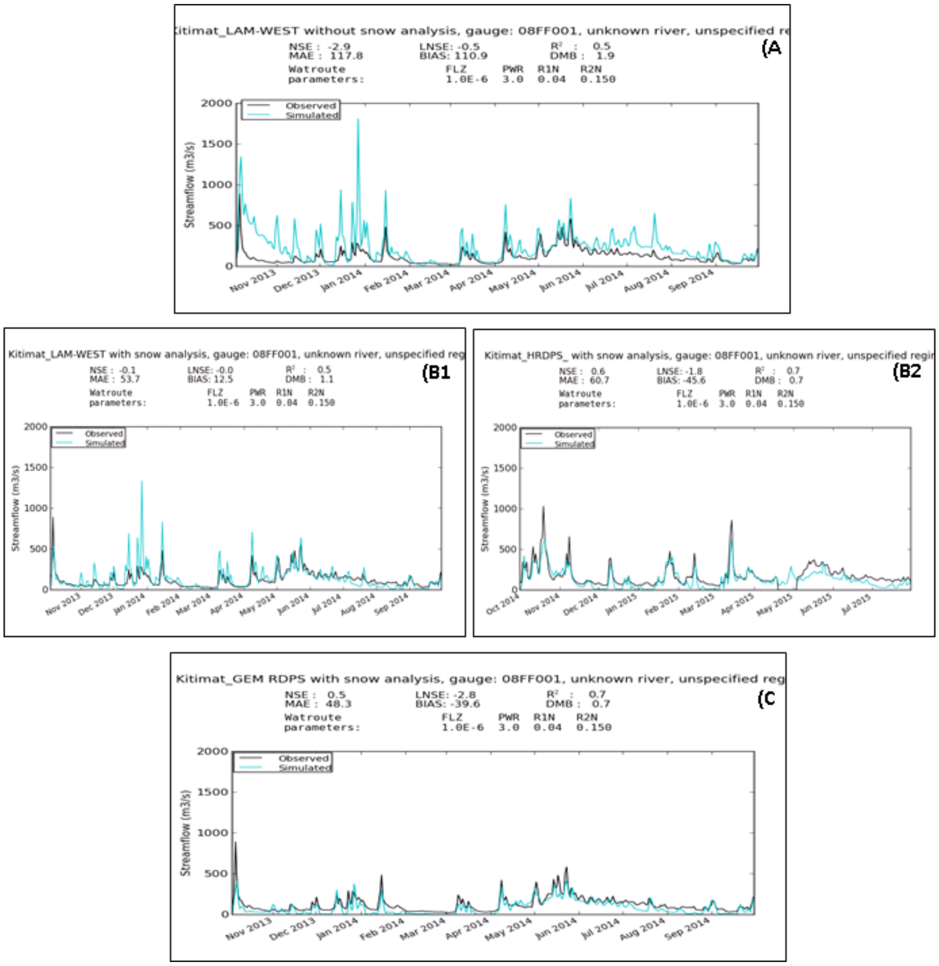

Figure 6. Comparison of simulated and observed mean daily streamflow from: (A) Kitimat station using LAM-WEST surface model without snow analysis for the period 2013-2014, (B1) Kitimat station using LAM-WEST surface model with snow analysis for the period 2013-2014, (B2) Kitimat station using HRDPS surface model with snow analysis for the period 2014-2015 and (C) Kitimat station using GEM RDPS land-surface model with snow analysis for the period 2013-2014.

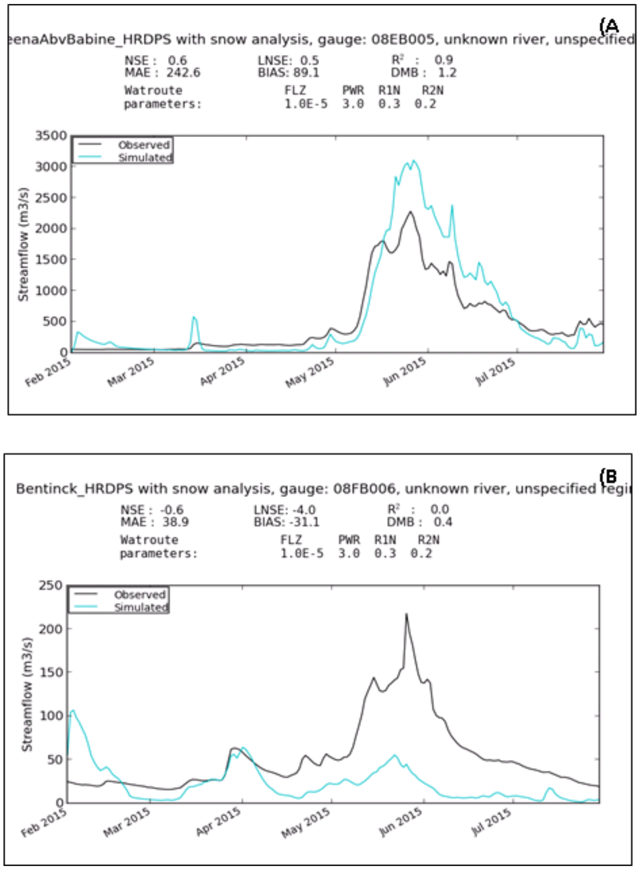

Figure 7. Comparison of simulated and observed mean daily streamflow using WATROUTE/HRDPS surface model with snow analysis from: (A) SkeenaAbvBabine and (B) Bentinck gauging stations for the period Feb.2015-Jul.2015

3.2 Performance of daily water temperature simulations

To test the performance of RBM on a daily time step, the water temperatures measurements at Kitimat, Bentinck and SkeenaAbvBabine gauging stations were used. For Kitimat station, the simulated water temperature series generally fell between the observations during the period between October and March when using HRDPS as surface model (Figures 8 A, B1, B") and the variability in water temperature was well simulated throughout the year (Figure 8). For all model configurations, water temperatures in spring were slightly overestimated, but overall for HRDPS the timing and magnitude of the rise in water temperature of the Kitimat river during summer were simulated realistically during the evaluation period (Figure 8 A, B) . The combined models have a BIAS ranged from -1.14 to 0.42°C and coefficient of determination values were above 0.87 (Figure 8). It was also observed that for the RDPS, the annual cycle in water temperature was simulated realistically; however, the steepness of the falling limb during August–October was on average too high and the decrease started too early in the season. This might be explained by an underestimation of the discharge peak for the Kitimat station during summer (reflected by negative BIAS; Figure 6C), and associated underestimation of the thermal capacity (Figure 8C).

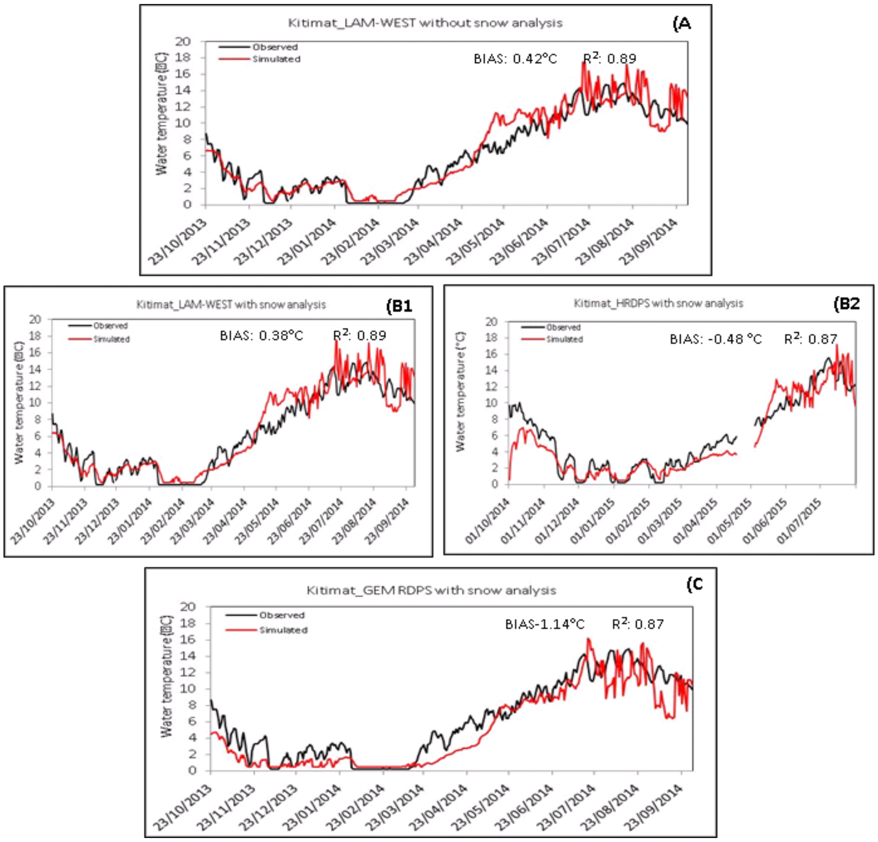

Figure 8. Comparison of simulated and observed mean daily water temperature from: (A) Kitimat station using LAM-WEST surface model without snow analysis for the period 2013-2014, (B1) Kitimat station using LAM-WEST surface model with snow analysis for the period 2013-2014, (B2) Kitimat station using HRDPS surface model with snow analysis for the period 2014-2015 and (C) Kitimat station using GEM RDPS land-surface model with snow analysis for the period 2013-2014.

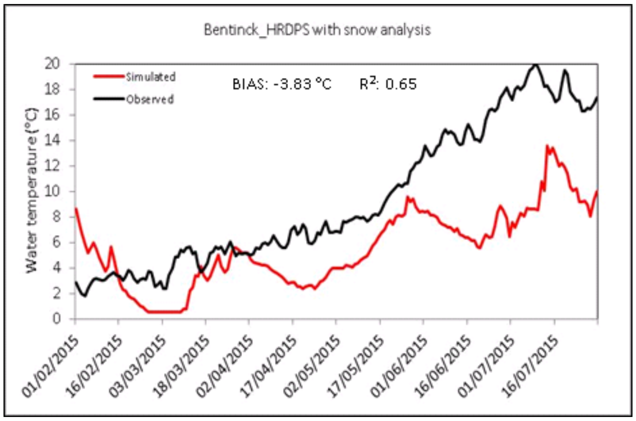

Figure 9. Comparison of simulated and observed mean daily water temperature using WATROUTE/HRDPS surface model with snow analysis from Bentinck gauging stations for the period Feb.2015-Jul.2015

The RBM output for Bentinck gauging station exhibited a pattern (Figure 9B) that is not consistent with that obtained by Kitimat. First, there is potentially some underestimation: during the validation period (Feb.-Jul. 2015), RBM simulates rapid decreases in water temperature in the winter months that are uncorrelated with observed temperatures. When examining the observed data, the later exhibit a lighter decline in the winter that the model can not capture very well. This underestimation can partially be explained by the length of observed data used for validation. It was also observed that the water temperature simulations are consistently relatively low to the observations.

For SkeenaAbvBabine gauging station, because of the non-availability of water temperature observed data, the results of RBM simulation are not shown.

3.3 Domain simulation

Since the primary area of interest for DFO is the watersheds draining directly into Douglas Channel and other fjords and inlets near Kitimat, and since the FVCOM model's requires freshwater boundary conditions, we can provide simulated streamflow in whole Kitimat subdomain for the period 1st-31st October 2013. The format of the WATROUTE output with a horizontal resolution of 2.5 km can be provided in text file format.

4. DISCUSSION & CONCLUSION

In the present study, we have used a physically based modelling approach with WATROUTE hydrological model and RBM water temperature model. The modelling approach was tested for three hydrological stations in the Pacific coast. Based on our analysis, we conclude that the coupled hydrological and water temperature modelling approach is suitable to simulate daily streamflow realistically by using HRDPS (LAM-WEST) with snow analysis as surface model and water temperature ($-3.89°C<BIAS<0.38°C$; $0.65<R^2<0.89$) over short (from 6 months to 1 year) periods. During summer a slight underestimation was found, which indicates that the modelling approach could have a potential for studying climate change and other anthropogenic impacts on daily streamflow and water temperature in relatively small river basins. Applied to the Salmon (subbasin Columbia), Yearsley (2012) concluded that the Variable Infiltration Capacity (VIC)/RBM modelling framework performs as well or better than statistical water temperature models and within the range of site-specific applications of process-based models. As site-specific was the focus of our study, local conditions such as effects of topography, vegetation and groundwater recharge, which can significantly influence river discharge and water temperature in small streams (e.g. Sridhar et al., 2004; Cristea and Burges, 2010) should be included in further studies. Simulated river flow can affect simulated water temperatures, especially during summer season (warm conditions). These results correspond with those obtained by van Vliet et al. (2011), Sinokrot and Gulliver (2000) and Bartholow (1991), who found a pronounced impact of river discharge on especially high temperatures. For water temperature, increasing the spatial resolution would probably improve the quality of the simulations, by decreasing the effect of headwater temperature estimates biases on the downstream reaches.

In conclusion, the physically based GEM/WATROUTE/RBM modelling approach is suitable to simulate realistically daily streamflow and water temperature at site specific. The modelling approach has potential to support water resources mangers in need of projected streamflow and water temperature for management decisions in the face, for example, of thermal pollution (anthropogenic effects) and climate change impacts for small river basins. The validation presented in this study was limited to three sites. To fully validate the preliminary conclusions of the present study, applications to other sites with longer time series would be useful. Also, it will be interesting to test the modified version of the Canadian Land Surface Scheme (CLASS, Verseghy, 1991; Verseghy et al., 1993) as well as the Soil, Vegetation, and Snow (SVS) Scheme to generate runoff for streamflow simulation.

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Table A.1. Setup procedure to build a new experiment for the WATROUTE executable

	Steps	Substeps	How?	Wiki page
Directory creation	**Initial preparation**			
	Make a new experiment directory	Inside a local directory (${path}/watroute): 1. Create two work directories ‘’experiments” and “trunk” 2. Inside ‘’experiments”, create one subdirectory of the experience name: ${path}/watroute/experiments/$Exp_name	1. mkdir experiments ; mkdir trunk 2. mkdir /$Exp_name	
	Getting the source code	The source code can be obtained from the svn subversion repository	svn checkout svn://mrbsvn.cmc.ec.gc.ca/mesh/watroute/trunk /${path}/watroute/trunk	Hydrology/ wat shed
	Compiling the code	1. Open ${path}/watroute/trunk 2. Open ${path}/watroute/trunk/utils The binaries produced are in: ${path}/watroute/trunk/bin	1. cmpl 2. cmpl	Hydrology/ wat shed
Input directory	**Individual files**			
	Prepare the input files	1. Create a subdirectory “input” in ${path}/watroute/experiments/$Exp_name 2. Open fst4shed_creation from ${path}/watroute/trunk/bin 3. Create the folder “tcl” inside fst4shed_creation 4. to use the former version, copy ${path}/watroute/trunk/bin/tcl to ${path}/watroute/trunk/fst4shed_creation/tcl 5. Open HydroSHEDStoFST_former.ksh and make the requested changes (see section 2 in wiki page) 6. Run HydroSHEDStoFST_former.ksh 7. Check the fields generated using SPI	1. mkdir input 3. mkdir tcl 4. cp tcl ${path}/watroute/trunk/bin/fst4shed_creation/tcl 5. nano HydroSHEDStoFST_former.ksh 6. HydroSHEDStoFST_former.ksh 7. SPI -field {SHED name}.fst	Hydrology/ wat shed
	Determine the outlet point	1. Determine the Local X and Local Y coordinates of the outlet point by opening field {SHED name}.fst in SPI	1. See details in wiki	Hydrology/ wat shed
	Create the shed files	1. To have the executable CreateShdFile.exe, compile the CreateShdFile.f90 located in ${path}/watroute/trunk/utils 2. Copy the CreateShdFile from ${path}/watroute/trunk/utils to your working directory 3. Create a subdirectory named ‘’templates’’ in your input file: ${path}/watroute/experiments/$Exp_name/input 4. Copy the CreateShdFile.dat from ${path}/watroute/trunk/templates to ${path}/watroute/experiments/$Exp_name/input/templates 5. Copy CreateShdFile.dat to your working directory and update its contents for your domain (see section 4.2.2 in wiki site) 6. Save the modified version of CreateShdFile.dat in	1. s.compile -o CreateShdFile -obj CreateShdFile.f90 -librmn rmn_015.1 2. cp CreateShdFile ${path}/watroute/experiments/$Exp_name/input/extras 4. cp CreateShdFile.dat ${path}/watroute/experiments/$Exp_name/input/templates 5. nano CreateShdFile.dat	Hydrology/ wat shed

		${path}/watroute/experiments/$Exp_name/input/extras 7. Running CreateShdFile.exe	7. CreateShdFile < CreateShdFile.dat	
	Initializing flows (the initial conditions of flow)	1. Go to ${path}/watroute/trunk/bin/ and open the file shed2flowinit.ksh and modify the shedfile (input) and the flowfile (output) according to wiki site to create the appropriate initial conditions file for the experiment 2. run shed2flowinit.ksh by typing its name 3. Go to your work directory ${path}/watroute/experiments/$Exp_name/inputs to be sure that your {flow_init_name}.fst is there. 4. Open the {flow_init_name}.fst by using SPI to check the fields generated	1. nano shed2flowinit.ksh 2. shed2flowinit.ksh 4. SPI - field {flow_init_name}.fst	Hydrology/ flow ICs/
	Initializing sfcmod2wat	1. Go to ${path}/watroute/trunk/bin/ and open the file run_sfcmod2wat.ksh and make the requested changes in export SfcLaLo, export WatShed, export workdir, export bindir, export ni, export nj. Replace "mez" by "Pollux". 2. run sfcmod2wat 3.Copy sfcmod2wat.fst from ${path}/watroute/trunk/bin/ to your work directory 4.Open the output shedfile (.fst) by using SPI to check the fields generated	1. nano run_sfcmod2wat.ksh 2. sfcmod2wat /cnfs/dev/mrb2/armn/armnmdi/sps/experiments/Kitimat_HRDPS_snowregr/output/output_2014100400/analysis/pm20141004000000-00-00_000000h ${path}/watroute/experiments/$Exp_name/input/extras/{SHED name}.fst sfcmod2wat.fst FLOW 4. SPI -field sfcmod2wat.fst	Hydrology/ hydro sfcmod2wat
	Templates files			
	Adjust values in event.evt_template	1. Create a subdirectory named ‘’templates’’ in your input file: ${path}/watroute/experiments/$Exp_name/input 2. Open event.evt_template from ${path}/watroute/experiments/$Exp_name/inputs/templates	1. mkdir templates 2. nano event.evt_template	Hydrology/ Watroute run
	Create yyyymmdd_REL.tb0	1. make adjustment on watroute.cfg if the Watroute domain contains no reaches (natural lake or controlled reservoir) to be processed 2. If a reach is to be processed, then: Copy yyyymmdd_REL.tb0 to your experiment directory: ${path}/watroute/experiments/$Exp_name/inputs/templates	1. nano watroute.cfg 2. cp ${path}/watroute/trunk/templates/yyyymmdd_REL.tb0 ${path}/watroute/experiments/$Exp_name/input/templates	Hydrology/ Watroute run
	Observation-based streamflow values			

		1. Assign the name PATHINPUT/strfw/DATE_str.tb0 to streamflowDataFile in ${path}/watroute/experiments/$Exp_name/input/templates/event.evt_template 2. Create a directory named ‘’ strfw’’ in ${path}/watroute/experiments/$Exp_name/input 3. Create a directory named ‘’ Qobs’’ in ${path}/watroute/experiments/$Exp_name/input/ 4.Download streamflow data (CSV format) of the period of interest and the station (s) of interest from HYDAT database: https://ec.gc.ca/rhc-wsc/default.asp?lang=En&n=9018B5EC-1 5. - Put the daily streamflow csv data in: ${path}/watroute/experiments/$Exp_name/input/Qobs/“CSV_CA” - Convert your csv data to text - Put the converted data in a new file named“ TXT_CA” - Insert a template “20000601_str.tb0” in Qobs (see the other available experiments) - Create a file “streamfiles” - Open the file “ ${Exp}_stations.txt” and put all the information relative to your hydrological station - Open create_obs2.py and make changes according to your data (e.g., start date, end date, etc) - Run create_obs2.py - Open “streamfiles” to find yyyymmdd_str.tb0 of each month of hourly data - Put the content of “streamfiles” in input/strfw **Notice**: Before running watroute, the observed data should be in hourly time steps and should be processed in Coordinated Universal Time (UTC). So a suitable conversion should be done in create_obs2.py (in line 266, make change of the hours that should be added, depending of the location of your station).	2. mkdir strfw 3. mkdir Qobs 5. - read_CA_streamflows.py - create_obs2.py	Hydrology/ Watroute run
Running Watroute	**Configuration file**			
	Configurate watroute	1. Copy watroute.cfg from ${path}/watroute/trunk/templates to ${path}/watroute/experiments/$Exp_name/ 2. Set all variable values according to section 1.2 in wiki site **Notice**: in watroute.cfg, Strtdate, should start one day before the		Hydrology/ Watroute run

		start date at which you want to simulate your streamflow		
	Controlling script			
	Run Watroute	1. Go to the directory ${path}/watroute/trunk/bin/ 2. Run run_water_budget.sh without modify anything	2. run_water_budget.sh ~ ${path}/watroute/experiments/$Exp_name	Hydrology/ Watroute run

Table A.2. Directory and subdirectories of a WATROUTE experiment

Directory	Sub-directory	Contents	Sub-contents
$Exp_name	input	$Exp_name _head.fst	
		Qobs	
		extras	CreateShdFile.dat*
			CreateShdFile*
			CreateShdFile.f90
			$Exp_name _head.fst
		Shed.fst@	$Exp_name _head_shed.fst
		flow_init.fst	
		sfcmod2wat.fst	
		strfw	yyyymmdd_str.tb0 for each month
		lake_levs	
		templates	event.evt_template
			yyyymmdd_REL.tb0
	output	rbm_input.fst	
		spl_rpn_cms	
		gridflow_cms	
		flow_init_mixed	
	post_processing		
	pre_processing		
	watroute.cfg		