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*Supplement of*

## **On the configuration and initialization of a large-scale hydrological land surface model to represent permafrost**

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## S1. Thermal Soil Properties

The thermal conductivity  $\lambda$  of organic and mineral soils are calculated using the concept of relative thermal conductivity  $\lambda_r$  that varies between 0 for dry soil and 1 for saturated soils (Côté and Konrad, 2005) as follows:

$$\lambda = \lambda_r[\lambda_{sat} - \lambda_{dry}] + \lambda_{dry} \quad (S1)$$

where

$$\lambda_r = \kappa S_r / [1 + (1 - \kappa) S_r] \quad (S2)$$

is a function of the level of saturation  $S_r$  (the total moisture content divided by the porosity  $\theta_p$  for mineral soils and by the retention capacity  $\theta_{re}$  for fully organic soils) and  $\kappa$  is an empirical coefficient that depends on soil texture and its water state as:

Unfrozen coarse mineral	$\kappa = 4.00$
Frozen coarse mineral	$\kappa = 1.20$
Unfrozen fine mineral	$\kappa = 1.90$
Frozen fine mineral	$\kappa = 0.85$
Unfrozen organic	$\kappa = 0.60$
Frozen organic	$\kappa = 0.25$

The dry thermal conductivity is calculated as a function of porosity  $\theta_p$  as:

$$\lambda_{dry} = a e^{b\theta_p} \quad (S3)$$

with  $a = 0.75$  and  $0.30$ ,  $b = -2.76$  and  $-2.0$  for mineral and organic soils respectively and  $\theta_p$  is the porosity, defined for organic soils based on sub-type (Table S1) and defined for mineral soils as a function of volumetric sand fraction ( $X_{sand}$ ) after (Cosby et al., 1984):

$$\theta_p = (-0.126 X_{sand} + 48.9)/100 \quad (S4)$$

The saturated thermal conductivity is calculated as:

$$\lambda_{sat} = \lambda_w \theta_p + \lambda_s (1 - \theta_p) \quad \text{for unfrozen soil} \quad (S5)$$

$$\text{or} \quad \lambda_{sat} = \lambda_i \theta_p + \lambda_s (1 - \theta_p) \quad \text{for frozen soil} \quad (S6)$$

where  $\lambda_w$ ,  $\lambda_i$ , and  $\lambda_s$  are the thermal conductivities of water, ice, and soil particles respectively.  $\lambda_s$  for mineral soils is calculated based on sand, fine (clay + silt), and organic content volumetric fractions using

a formula similar to Equation (2) in the main manuscript. In case of supplying an organic fraction in a mineral soil (M-org configurations), the lower density of organic matter ( $1.3 \text{ gm}^{-3}$ ) compared to soil minerals ( $2.65 \text{ gm}^{-3}$ ) affects the volumetric fractions and consequently the thermal and hydraulic properties. For fully organic soils the value is taken directly as given in Table S1 depending on the peat sub-type of the layer.

*Table S1 Important Thermal and hydraulic properties for the soil material and moisture*

Soil Component	Heat Capacity $C \text{ [Jm}^{-3}\text{K}^{-1}]$	Thermal Conductivity $\lambda \text{ [Wm}^{-1}\text{K}^{-1}]$	Porosity $\theta_p \text{ []}$	Retention Capacity $\theta_{re} \text{ []}$	Minimum water content $\theta_{min} \text{ []}$	Saturated Hydraulic Conductivity $K_{sat} \text{ [ms}^{-1}]$
Water	$1.93 \times 10^6$	0.57	-	-	-	-
Ice	$4.19 \times 10^6$	2.24	-	-	-	-
Sand	$2.13 \times 10^6$	2.50 saturated	-	-	0.04	Equation S4
Fine (clay+silt)	$2.38 \times 10^6$	0.275 dry	-	-	0.04	Equation S4
Fibric peat (type 1)			0.93	0.275	0.04	$2.8 \times 10^{-4}$
Hemic peat (type 2)	$2.5 \times 10^6$	0.25	0.88	0.62	0.15	$2.0 \times 10^{-6}$
Sapric peat (type 3)			0.83	0.705	0.22	$1.0 \times 10^{-7}$

At any particular time step, the volumetric fractions of water and ice are variable and depend on the water and energy balance calculations. They are used to update the soil thermal and hydraulic properties at the beginning of the next time step. Even if all the water drains or freezes, a remainder of 4% by volume remain in liquid form in all layers above bedrock for mineral soils but this figure is higher for hemic and sapric peat (see Table S1 above). Below bedrock (denoted by SDEP level), the soil thermal properties are taken as sand and it remains dry all the time (zero water content). Further details are given in CLASS manual (Verseghy, 2012).

## S2. Detailed Description of Selected Study Sites

### S2.1 Jean Marie River

The Jean Marie River (JMR) is a tributary of the main Mackenzie River Basin (Figure 3a) in the Northwest Territories (NWT) in Canada. Its mouth is located upstream of Fort Simpson where the Liard River joins the main Mackenzie River. The gauged area at WSC station 10FB005 at the river intersection with Highway 1 is about  $1240 \text{ km}^2$ . The basin is dominated by boreal (deciduous, coniferous and mixed) forest on raised peat plateaux and bogs. The basin is located in the sporadic permafrost zone where permafrost underlies

few spots only and is characterized by warm temperatures ( $> -1^{\circ}\text{C}$ ) and limited ( $<10\text{m}$ ) thickness (Smith and Burgess, 2002).

The nearest Environment and Climate Change Canada (ECCC) weather station is located at Fort Simpson to the north of the basin. The Canadian Climate Normals (1981–2010, ECCC) at Fort Simpson indicates that the mean annual temperature is  $-2.8^{\circ}\text{C}$  with temperatures generally below freezing during October to April while a maximum summer temperature of  $17.4^{\circ}\text{C}$  is reached in July. Mean annual precipitation is about 388 mm/year, of which around 60% falls as rain while the rest is snowfall.

Water Survey of Canada (WSC) has a good streamflow record at this site for the period 1972-2015. The basin is snowmelt dominated with flow peaks normally occurring in May/June with some years having secondary summer peaks. The mean annual streamflow at the station over the period 1980-2015 is  $5.5\text{ m}^3/\text{s}$ , while the highest recorded streamflow reached  $211\text{ m}^3/\text{s}$  on July 3, 1988. Baseflow is usually small but the river does not run completely dry in winter despite its surface freezing.

For the MESH model configuration, the gauged part of the basin is covered by 14 grid cells of the MRB model grid at a  $0.125^{\circ} \times 0.125^{\circ}$  resolution, and can thus be hydrologically assessed in terms of the quality of the streamflow simulations. However, this is not the main focus of this study. Because of the inherent transferability of parameters afforded by the GRU approach, parameters for MESH are taken from calibrations of the adjacent Liard sub-basin (Elshamy et al., in preparation).

The basin and adjacent basins (e.g. Scotty Creek) have been subject to extensive studies because the warm, thin, and sporadic permafrost underling the region has been rapidly degrading (Calmels et al., 2015; Quinton et al., 2011). The region is vulnerable to permafrost thaw, which is changing the landscape of the region, the vegetation, and wildlife habitat with significant implications for First Nations livelihoods and access to their cultural resources. Collapse of forested peat plateaux and their degradation into wetland areas has been reported by several researchers (e.g. Calmels et al., 2015; Quinton and Baltzer, 2013)

Several permafrost-monitoring sites have been established in and around the basin mostly as part of the Norman Wells to Zama pipeline monitoring program launched by the Government of Canada and Enbridge Pipeline Inc. in 1984-1985 (Smith et al., 2004). The sites were installed to investigate the impact of the pipeline on the permafrost and terrain conditions. Details of the sites are given in Table 1 while Figure 3a (both in the main manuscript) shows their locations. Figure S1 shows the temperature envelopes for the available years of record. This study uses data from sites 85-12A and 85-12B using Cables T4, as they are the least affected by the pipeline, being in excess of at least 20m from the right of way of the pipeline

location. Site 85-12A has no permafrost while site 85-12B, in close proximity, has a thin (3-4m) permafrost layer with ALT of about 1.5m as estimated from soil temperature envelopes over the period 1986-2000. All other monitoring points on Figure 3a have no permafrost conditions since their records began in the 1980s and 1990s. The sites are located on a ground moraine landform with open black spruce, ericaceous shrubs, and moss-lichen woodland on a peat plateau (Smith et al., 2004). The difference in permafrost conditions is possibly related to the thickness of the peat as shown in the borehole logs (Smith et al., 2004). Borehole 85-12A-T4 has a little over 1m thick layer of peat while borehole 85-12B-T4 has close to 5m peat providing more insulation that keeps the ground from thawing during summer.

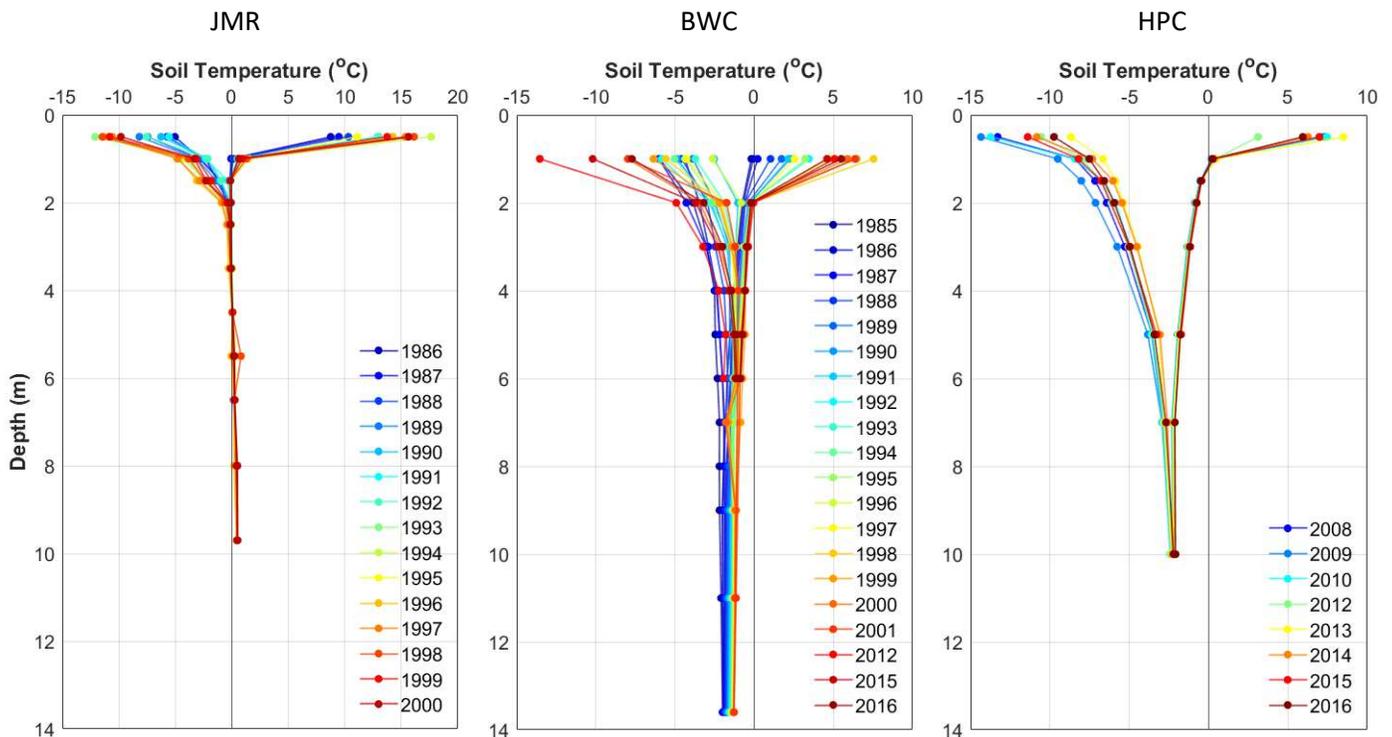


Figure S1 Observed Temperature Envelopes at the three selected sites

## S2.2 Bosworth Creek (Norman Wells)

Bosworth Creek (BWC) is a small basin (126 km<sup>2</sup>) draining from the northeast to the main Mackenzie River near Norman Wells (Figure 3b). Permafrost monitoring activities started in the region in 1984 with the construction of the Norman Wells to Zama buried oil pipeline (as described in the Jean Marie River section). The basin is dominated by boreal (deciduous, coniferous and mixed) forest. It is located in the extensive discontinuous permafrost zone with relatively deep active layer (1-3 m) and relatively thick (10-50m) permafrost (Smith and Burgess, 2002)

There is an ECCC weather station nearby at Norman Wells with complete temperature and precipitation records from 1980. The Canadian Climate Normals (1981–2010, ECCC) at Norman Wells indicate that the mean annual temperature is  $-5.1^{\circ}\text{C}$  with temperatures generally below freezing during October to April while the maximum summer temperature of  $17.1^{\circ}\text{C}$  is reached in July. Mean annual precipitation is about 294 mm/year, of which around 60% falls as rain while the rest is snowfall.

Similar to the Jean Marie River Basin, the streamflow is dominated by snowmelt with a peak in May and a secondary summer peak in some years. WSC Gauge 10KA007 is at the outlet of the basin near its confluence with the Mackenzie River and has records over two periods 1980-1994 and 2009-2016. The mean annual discharge over the available period of record is  $0.67\text{ m}^3/\text{s}$  with peaks ranging normally between 2.5 and  $15\text{ m}^3/\text{s}$ . The highest daily flow on record reached about  $20\text{ m}^3/\text{s}$  in May 1991. There is a visible baseflow component for this basin. The basin only covers portions of three grid cells of the MRB model grid (Figure 3b), thus it is not expected to have adequate simulation for streamflow comparisons.

The basin itself has not been the focus of previous hydrological studies, but there are several permafrost studies of Norman Wells, being at the Northern end of the Zama pipeline. Sapriza-Azuri et al. (2018) used cable T5 at the pump station site (84-1) to investigate the appropriate soil depth and initial conditions for their own permafrost simulations, which serve as a pre-cursor for this current study. They recommended a soil depth of a least 20m to ensure that the simulated DZAA is within the soil profile. However, they based their analysis on cable T5, which is within the right of way of the pipeline and is likely to be affected by its construction/operation.

There are several thermal monitoring sites within and close to the basin and the adjacent Canyon Creek basin to its southeast – Table 1 in the main manuscript. There are also a few thaw tubes, but their records are short and intermittent. We focus on the Norman Wells pump station site (84-1) and for this study we choose cable T4 as it is more likely to reflect the natural permafrost conditions being out of the right of way of the pipeline. It has a continuous record since 1985 (Smith et al., 2004; Duchesne, personal communication, 2017).

### S2.3 Havikpak Creek

Havikpak Creek (HPC) is a small arctic research basin (about  $15\text{ km}^2$  in area) located in the eastern part of the Mackenzie River basin delta, 2km north of Inuvik Airport ( $68^{\circ}18'15''\text{ N}$ ,  $133^{\circ}28'58''\text{ W}$ ) in the Northwest Territories (NWT) (Figure 3c). The basin is dominated by sparse taiga forest and shrubs, has a cold sub-

arctic climate and is underlain by thick permafrost (>300m). The basin is characterized by mild slopes and has an elevation ranging between 60-240m (Krogh et al., 2017).

There is an ECCC weather station at nearby Inuvik Airport with hourly temperature record from 1980 and daily precipitation record from 1960. The Canadian Climate Normals (1981–2010, ECCC) at Inuvik indicates that the mean annual temperature is -8.2°C with temperatures generally below freezing during October to April while a maximum summer temperature of 14.1°C is reached in July. Mean annual precipitation is about 241 mm/year; close to half of which is rainfall while the rest falls as snow.

The streamflow record of the basin is dominated by snowmelt with no winter flow and some small summer events. The diminished winter flow is due to the lack of groundwater contribution as the cold climate prevents the formation of lateral taliks (Connon et al., 2018). Streamflow at the outlet of the basin at WSC gauge 10LC017 has been measured since 1995. The mean annual streamflow at the outlet is about 0.07 m<sup>3</sup>/s with a maximum of 4.65 m<sup>3</sup>/s reached in the summer of 2000. The summer peak discharge varied greatly between 0.7 and 4.0 m<sup>3</sup>/s over the period 1995-2017. However, the basin covers portions of only two grid cells of the MRB model grid (Figure 3c) and therefore is not expected to have adequate simulation for streamflow comparisons.

The basin has been subject to several hydrological studies, especially during the Mackenzie GEWEX Study (MAGS). For example, Marsh et al. (2002) studied the water and energy fluxes from HPC for the important 1994/95 hydrological year. More recently, Krogh et al. (2017) modelled its hydrological and permafrost conditions using the Cold Regional Hydrological Model (CRHM) (Pomeroy et al., 2007). They integrated a ground freeze/thaw algorithm called XG (Changwei and Gough, 2013) within CRHM to simulate the active layer thickness and the progression of the freeze/thaw front with time but they did not attempt to simulate the temperature envelopes or DZAA.

In terms of permafrost-related measurements, soil temperature envelopes are available at Inuvik Airport forest and bog sites 01TC02 and 01TC03 respectively. Ground temperatures are measured with multi-sensor temperature cables installed in boreholes going down to 10m and 6.5m in depth at 01TC02 and 01TC03 respectively (Smith et al., 2016). Temperature sensors failed on the bog site (01TC03) in 2010. The site was replaced by 12TC01, which shares the same characteristics. In addition, there are three thaw tubes at Inuvik Upper Air Station (90-TT-16) just to the west of the basin, at HPC proper (93-TT-02), and at the Inuvik Airport bog site (01-TT-03) measuring the active layer depth and ground settlement (Smith et al., 2009). The land form and vegetation at Inuvik Airport forest site (01TC02) is described as fluted till

plain with open black spruce trees while the other site (01TC03) is an open bog between ridges on the fluted till plain with scattered shrubs in an open bog. The HPC thaw tube is located in a back spruce forest (Smith et al., 2009).

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