

## Consortium for Permafrost Ecosystems in Transition: Traversing the Southern Margin of Discontinuous Permafrost with Hydrological, Ecological and Remote Sensing Research, Northeastern British Columbia and Southwestern Northwest Territories

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### Introduction and Project Scope

The southern margin of discontinuous permafrost, over a region comprising northeastern British Columbia (NEBC) and southwestern Northwest Territories (NWT), has experienced rising air temperatures in recent decades (Quinton et al., 2009). Analysis of streamflow records from gauged basins in the lower Liard River valley of this region shows that discharge is also increasing over a similar period despite no apparent changes to total annual precipitation (St. Jacques and Sauchyn, 2009; Connon et al., 2014). The land cover of this region mainly consists of upland and lowland forests and wetlands (e.g., bogs and fens), with a portion of the forested land cover underlain by permafrost. Bogs and fens have unique hydrological functions. Bogs are storage features whereas fens are channels that transport water laterally through the landscape. Degradation of permafrost ultimately leads to the conversion of forested plateaus to wetlands (Baltzer et al., 2014). Reported estimates of permafrost degradation for this region indicate that the change in aerial extent of permafrost coverage (i.e., decrease in forest/wetland expansion) is 28% from 1970 to 2012 (Coleman et al., 2015), 27% from 1947 to 2008 (Chasmer et al., 2010) and up to 50% from ~1950 to 2000 (Beilman and Robinson, 2003). Accordingly, various studies have attributed rising streamflow in gauged basins over the region to both shrinking aerial extent and thickness of

permafrost (e.g., St. Jacques and Sauchyn, 2009; Quinton and Baltzer, 2013a; Connon et al., 2014).

In addition to correlated trends among rising air temperature and streamflow records concomitant with estimates of permafrost loss, industrial activities are occurring or have historically occurred over parts of the region in the form of exploration and extraction for oil and natural gas. These influences add extra complexity to understanding and predicting future hydrological consequences of climate warming over the region. Industrial activities have two major implications for land cover change and water resources availability: 1) permanent impacts of linear disturbances (i.e., deforested corridors created for seismic exploration, winter roads and pipelines; Lee and Boutin, 2006) and 2) industrial uses of large volumes of surface water for hydraulic fracturing of shale gas in NEBC (Hayes, 2010; Johnson, 2010). Linear disturbances have been made throughout the landscape of the NEBC–NWT border region since at least the 1970s. There is evidence that the removal of vegetation for linear disturbances significantly alters the thermal properties of the ground so much that, over time, this leads to permafrost-free corridors (Williams and Quinton, 2013; Braverman and Quinton, 2016). It has been suggested that the permafrost degradation along these corridors imposes surface water flow paths over the landscape, which connect forest and wetland land cover types (i.e., permafrost and permafrost-free areas), accelerate permafrost thaw, and potentially promote wetland drainage along topographic gradients (Williams et al., 2013). In terms of hydraulic fracturing present in NEBC, high volumes of water and other materials are injected into the ground to gain access to trapped geological deposits of shale gas. Johnson

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**Keywords:** *British Columbia, permafrost, environmental change, linear disturbances*

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(2010) and Hayes (2010) report that an estimated 1200 to >4000 m<sup>3</sup> of water are needed per fracture, which among other environmental concerns, represents a major demand on surface water and groundwater availability. This significant industrial demand must be managed effectively relative to the regional water balance, local community needs and considerations for future availability (Johnson, 2010).

Accurate estimation of future water resources in the NEBC–NWT border region is of interest for industry, community groups and governments across the region, as it will enable them to promote sustainable water use among users, assist in environmental change adaptation strategies and mitigate environmental impacts from climate warming and industrial development (e.g., Government of the Northwest Territories, 2008; Johnson, 2010). However, scientific knowledge of the changing hydrology of this region under coupled climate warming and industrial impact scenarios is relatively limited. It is commonly recognized among industry, community and government stakeholders that this issue is complicated by a lack of baseline and continuous hydrological monitoring data. Additionally, relatively few scientific studies have been completed to understand climate-driven and industrial impacts to land cover change and water availability across the region. Consequently, present efforts to apply hydrological models to the estimation of future water availability under varied scenarios of industrial disturbance and climate warming are subject to considerable uncertainty. Modelling efforts are further complicated by a lack of publicly available land cover datasets, such as detailed wetland and topography maps, as many current products are either outdated, inaccurate or developed at insufficient spatial resolutions.

The Consortium for Permafrost Ecosystems in Transition (CPET) was formed in 2015 among academic researchers, industry partners, and community and government groups

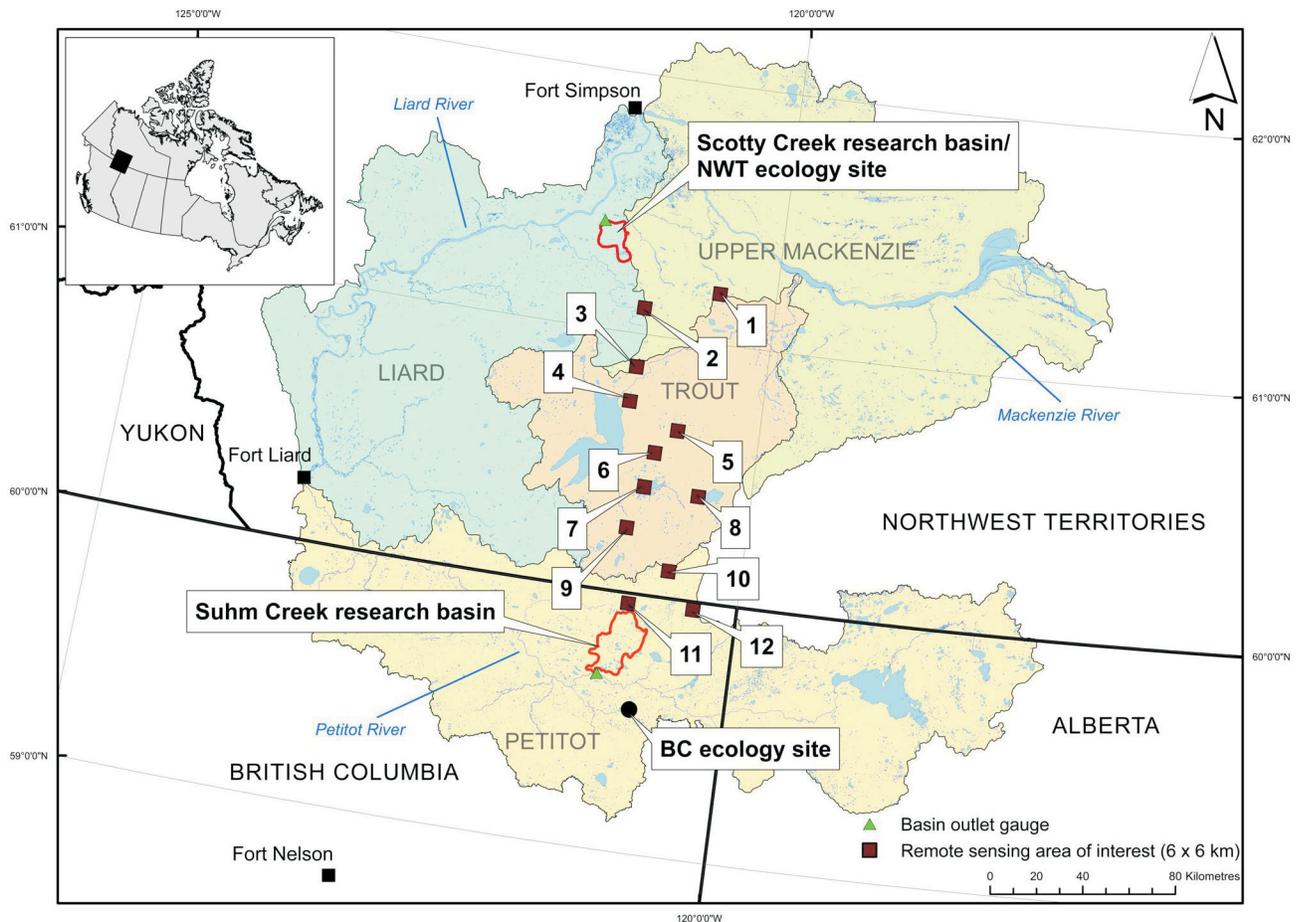
to address the aforementioned issues being faced by the NEBC–NWT border region. The long-term goal of CPET is to produce robust scientific knowledge of, and datasets on, climate-driven and industrial-imposed environmental changes to reduce uncertainty of water resources modelling. The CPET has five science objectives, which are listed in Table 1. The purpose of this paper is to summarize and report on CPET progress to date from 2015. For an extended project description and a literature synthesis on the science background of CPET, the reader is referred to Quinton et al. (2016).

## Development of Study Sites

The CPET research activities are completed over an approximately 175 km transect oriented north-south, which traverses the zone of discontinuous permafrost in southwestern NWT and northeastern BC (Figure 1). Field studies are concentrated at two research basins, which form latitudinal end members of the study region. Scotty Creek research basin (north) was established prior to the formation of CPET. Suhm Creek research basin (south) was established by CPET as a research site in 2015–2016 to act as a paired basin to Scotty Creek. The ongoing development of instrumentation capacity and datasets for Suhm Creek research basin is anticipated as a key legacy of CPET. From a hydrological modelling perspective, the development of a paired research basin to the south of Scotty Creek is a major advantage for developing and evaluating models at sites representing different latitudinal positions along the southern margin of discontinuous permafrost. It is noted that a significant difference between Scotty Creek and Suhm Creek basins is that Scotty Creek has no industrial presence, other than linear disturbances from prior to 1985, whereas Suhm Creek is representative of current industrial activity in NEBC (e.g., shale gas exploration in the Horn River geological basin). This allows for insights into as-

**Table 1.** Five science objectives of the Consortium for Permafrost Ecosystems in Transition (CPET).

<b>Objective 1</b>	Map the changing spatial distribution of permafrost, wetland and forest coverage over the study area using aerial photography, satellite images and light detection and ranging (LiDAR) images.
<b>Objective 2</b>	For different ground thaw and moisture conditions, conduct field studies to improve the understanding of the volume and timing of runoff from a) peat plateau–bog complexes and b) the adjacent channel fens, which convey the runoff that they receive from plateau-bog complexes to streams and rivers. For each setting, the water flux and storage processes that control runoff will be examined.
<b>Objective 3</b>	Simulate the major water flux and storage processes controlling runoff from the plateau-bog complexes using the cold regions hydrological model (CRHM) and the Raven hydrological modelling framework, and, where needed, make improvements to both models based on the improved process understanding arising from objective 2.
<b>Objective 4</b>	Improve the ability to characterize permafrost impacts at larger scales through field investigation and subsequent adaptation of the northern ecosystem soil temperature (NEST) regional-scale permafrost model to handle the unique thaw response of bogs, fens and plateaus.
<b>Objective 5</b>	Use information generated from the improved hydrological models (in objective 3) and the permafrost model (in objective 4) to estimate future quantities of runoff and surface water storage within boreal and subarctic landscapes with discontinuous permafrost under possible scenarios of climate warming and human disturbance.



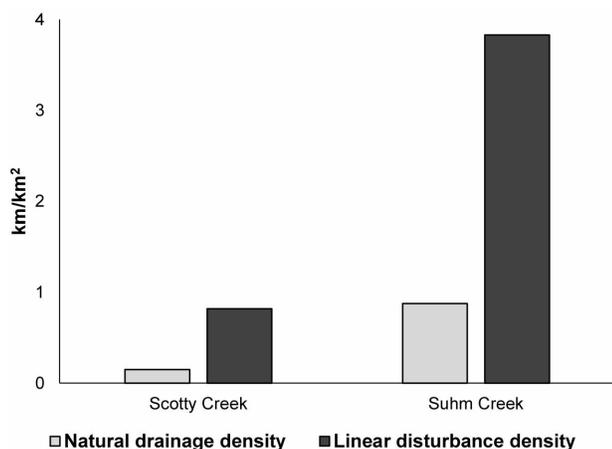
**Figure 1.** The Consortium for Permafrost Ecosystems in Transition (CPET) focuses on a north-south oriented study region traversing the southern margin of discontinuous permafrost (refer to Heginbottom and Radburn, 1992), northeastern British Columbia (BC) and south-western Northwest Territories (NWT). Field studies are concentrated at Scotty Creek and Suhm Creek research basins and additional observations are done at remote sensing areas of interest over the region. Note: streamflow gauge indicated for Suhm Creek is planned for installation during the CPET project but had not been installed at the time of publication. Base maps of watershed boundaries (red line) and water features are from the national hydro network (GeoBase®, 2014).

sessing impacts of industrial activities on basins in the zone of discontinuous permafrost. For example, this is demonstrated by the contrast in linear disturbance densities over Scotty Creek and Suhm Creek research basins shown in Figure 2.

### Scotty Creek

Scotty Creek basin is estimated to be approximately 140 km<sup>2</sup> and drains into the Liard River. Discharge from the basin has been measured continuously since 1996 by the Water Survey of Canada (Connon et al., 2014). The basin is located approximately 50 km south of Fort Simpson, NWT. The topography is relatively flat (~250 m relief) and land cover is dominated by upland forest, treed plateaus, flat bogs and channel fens (for further description, refer to Quinton et al., 2011; Chasmer et al., 2014). Approximately half the basin consists of peat plateaus, bogs and fens. Research involving data from field studies, automated instruments and remote sensing has been conducted at Scotty

Creek continuously since 1999. A growing body of scientific literature regarding hydrology of the discontinuous permafrost zone has been produced from this site, giving important insights for hydrological modelling. For example, understanding the functions of major land cover types (e.g., peat plateaus, channel fens and flat bogs) and their roles in runoff generation (e.g., Quinton et al., 2003; Wright et al., 2009), linkages between land cover change and streamflow (e.g., Connon et al., 2014), hydraulic properties of peatlands (e.g., Quinton and Baltzer, 2013b) and ecological responses to permafrost thaw (e.g., Patankar et al., 2015). A significant amount of infrastructure is currently in place at Scotty Creek, including a simple field camp for researchers (e.g., tents) and an array of automated instrumentation measuring climate and hydrological variables across different land cover types (e.g., bogs, fens and peat plateaus). These instruments measure variables such as precipitation, air temperature, relative humidity, wind speed, incoming and outgoing radiation, snow height, soil



**Figure 2.** Linear disturbance densities for Scotty Creek and Suhm Creek research basins (Northwest Territories and British Columbia, respectively) compared to natural drainage densities. Data for Scotty Creek is from Quinton et al. (2009). Linear disturbance densities for Suhm Creek are estimated from digitizing disturbances visible within a 143 km<sup>2</sup> sample of the basin using high resolution airphotos (<1 m). The drainage density of Suhm Creek is calculated using stream network length (obtained from Natural Resources Canada as a GIS vector layer) relative to the corresponding estimated basin area.

moisture and soil temperature at sites across the basin. A large volume of field sampling has been conducted at Scotty Creek, including measurements of active layer depth and talik formation (e.g., using ground penetrating radar), snow water equivalent, soil moisture and vegetation properties (e.g., leaf area index [LAI]).

### Suhm Creek

Suhm Creek basin is approximately 150 km northeast of Fort Nelson, BC, and drains into the Petitot River, which flows into the Liard River at Fort Liard (Figure 1). Suhm Creek basin is estimated to be 365 km<sup>2</sup> and there is ~200 m of topographic relief over the basin. Johnson (2010) conducted a review of basic hydrological modelling needs in the NEBC region (e.g., Suhm Creek) and identified key information gaps necessary for modelling. Johnson (2010) included 1) delineation of wetlands to identify proportions of fens and bogs; 2) knowledge of permafrost spatial distribution; 3) climate monitoring for major land cover types; 4) stream gauging; 5) water table measurement; and 6) topography data. For example, identifying the proportions of land cover types is important for modelling basin runoff because different land cover types have been shown to control unique runoff responses (Quinton et al., 2003). Specifically, it has been demonstrated that an increased proportion of bogs is inversely related to runoff, whereas a greater proportion of fens is positively correlated with runoff (Cannon et al., 2014). Although the types of land covers are relatively similar between Suhm Creek and Scotty Creek basins (mixed forested peatlands and wetlands), work to

characterize the differences in distributions of these land covers is in progress.

Much of the data requirements for hydrological modelling identified by Johnson (2010) have been addressed for Scotty Creek basin (Quinton et al., 2016), however, significant work is necessary to address these needs at Suhm Creek basin. As such, ongoing work is being conducted at Suhm Creek to address these gaps by installing automated instruments, completing field sampling and obtaining remote sensing datasets. Various instrumentation has been installed in the basin in 2015–2016 to provide continuous monitoring data of hydrological variables. Specifically, two climate monitoring stations were installed in late 2015 with analogous measurement capabilities to those at Scotty Creek basin. One climate station is located in a forested peat-plateau and the other is in an open wetland site. Data from these stations are used to characterize energy budgets of each land cover type. Pressure transducers have also been deployed at six nodes of Suhm Creek basin to measure water level and to assist in understanding the flow routing of streams over the basin and parameterize routing in distributed hydrological models. Installation of an automated stream discharge gauge near the outlet of Suhm Creek at Petitot River is also planned for the future to monitor total basin discharge (Figure 1). In terms of field sampling, distributed measurements are being done along transects of peat plateaus during site visits to Suhm Creek basin to determine permafrost presence relative to forested land cover and characterize depth to permafrost relative to distances from forested edges. The CPET researchers have obtained remote sensing datasets over Suhm Creek basin and work is being completed to map both forest and wetland land covers at high resolutions, similar to that of Scotty Creek basin (Chasmer et al., 2014). A light detection and ranging (LiDAR)-derived digital elevation model has also been obtained and can be used to estimate surface water pathways along topographic gradients.

### Remote Sensing Areas of Interest

In addition to field studies and data development of Suhm Creek and Scotty Creek basins, remote sensing areas of interest (AOI) have been established along a north-south configuration in the NEBC–NWT border region (Figure 1). These AOI connect the two research basins and enable sampling of land cover distributions along a latitudinal distribution over the southern margin of discontinuous permafrost (Figure 1). Each of the 12 AOI has a footprint of 36 km<sup>2</sup> (432 km<sup>2</sup> total area). Imagery stacking over these sites includes recent Landsat 8 (30 m resolution) and WorldView-1 and -2 (50 cm resolution) datasets and historical aerial photographs acquired in 1970–1971 (1.2 m resolution). Detailed statistical characterization of the land covers within these AOI is being developed at high resolutions, providing information on proportions of major land cover

types, and changes to these land cover types over a 40-year period. For example, one aspect of this work is examining changes to the total areas of forested plateaus and bogs. This can be useful as an indicator of decreased permafrost areal extent over time because the total area of bogs increases as plateaus underlain by permafrost decrease (Beilman and Robinson, 2003). Also within the remote sensing AOI, linear disturbance densities (Figure 3) and proportions of land cover intersected by these disturbances are being mapped. For example, Figure 3 illustrates the distribution of linear disturbance densities across selected remote sensing AOI of the study region.

## Progress Toward Science Objectives

### Assessing the Rate and Pattern of Permafrost Loss and Related Vegetation Change Using Remote Sensing

Analysis of satellite remote sensing datasets acquired over Scotty Creek and Suhm Creek research basins and remote sensing AOI commenced in 2015–2016 to determine rates and spatial extent of forest and bog changes over a 40-year period. From these, information on permafrost degradation is inferred from the changing vegetation composition. A very large coverage of spatial information is being generated from analysis of these remote sensing datasets providing robust estimates of land cover change across the NEBC–NWT region. Unlike previous small-scale estimates of change using remote sensing change detection (e.g., Chasmer et al., 2010), this work involves distributed sampling across the discontinuous permafrost region. To support this work, field verification was conducted in 2016 to validate permafrost presence according to vegetation distribution and ensure correct identification of land cover types during visual and automated interpretation of remote sensing images.

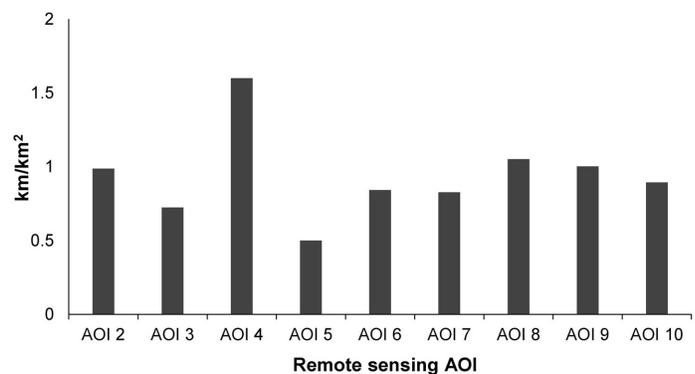
### Field Studies on Water Flux and Storage Processes

The CPET is using modelling as a tool for hypothesis testing at local scales to evaluate the efficacy of conceptual models developed from field observations, which describe specific hydrological processes. These local predictions of hydrological processes can then be upscaled to estimate hydrological fluxes over an entire basin. A significant amount of field studies was completed at Scotty Creek research basin in 2015–2016 and prior to the formation of CPET (Quinton et al., 2016), from which conceptual models of local-scale hydrological processes are being developed. For example, in the past year sampling was done at points throughout Scotty Creek basin to survey talik formation (unfrozen layer within permafrost ground) and frost table measurements. These data are applicable to parameterizing subsurface water flow and con-

nectivity within computational models. Very high resolution imagery (3 cm) was gathered from fixed-wing and rotary unmanned aerial vehicle (UAV) platforms for specific areas of interest within Scotty Creek research basin, including multispectral, thermal and infrared sensors. These data are used to develop very high resolution elevation products and identify surface temperatures of land cover features. This information contributes toward development of hydraulic roughness algorithms for modelling runoff between land cover types (e.g., isolated bogs and interconnected bogs). Data are now being analyzed from pressure transducers installed along stream nodes in Scotty Creek and Suhm Creek research basins in 2015–2016 to characterize hydrological routing. Finally, data are being analyzed from sap flow sensors installed on trees at Scotty Creek and a site near Suhm Creek (NWT and BC ecology sites on Figure 1) in 2015–2016 to characterize evapotranspirative fluxes over forested areas underlain by permafrost for inclusion in hydrological modelling calculations.

### Development and Testing of Hydrological Models to Simulate Water Flow and Storage

The CPET uses both the cold regions hydrology model (CRHM; Pomeroy et al., 2007) and Raven model (The Raven Development Team, 2014). Knowledge developed from field studies at Scotty Creek is being incorporated to parameterize these models to predict hydrological processes over local and basin scales. Both CHRM and Raven are object-oriented frameworks developed for simulating the energy and water balance of hydrological response units (HRU). The HRU corresponds to a spatial footprint of similar biophysical features and processes, in which mass and energy balances can be generalized (Pomeroy et al., 2007). Therefore, in a given HRU, a model can be parameterized with a single set of parameters and state variables. Important achievements were made in 2015–2016 to parameterize HRU in hydrological models, building off existing work. The CRHM computations of snowmelt, active



**Figure 3.** Linear disturbance densities for selected remote sensing areas of interest (AOI; 36 km<sup>2</sup> each) shown in Figure 1, numbered from north to south (Northwest Territories to British Columbia). Data are determined from digitizing visible seismic lines, winter roads and pipelines within 50 cm resolution WorldView-1 and -2 images.

layer thaw and subsurface flux have been conducted for Scotty Creek at bogs, fens and plateaus (Quinton et al., 2016). The current focus for Scotty Creek basin is on model development of these computations within the Raven platform.

## Conclusion

Industry, government and community groups in the NEBC–NWT border region acknowledge that there is a lack of monitoring data related to water resources. As a result, there are currently high levels of uncertainty in existing hydrological modelling tools for predicting water resources availability in the future under climate warming and industrial development scenarios. The CPET is filling this gap by developing new science-based conceptual and computational models to predict future permafrost thaw and determine the implications for water resources availability. This information is integral to plan for, and adapt to, impacts of permafrost thaw under varied scenarios. For example, the knowledge generated by CPET can be applied to limit damage to infrastructure caused by permafrost thaw (Government of the Northwest Territories, 2008) or be applied so that industry can confidently plan future operations, such as hydraulic fracturing, based on available water supplies (Johnson, 2010).

## Next Steps

The CPET work in 2016–2017 will build on existing knowledge and continue development of study sites to focus on 1) permafrost modelling and 2) basin-scale hydrological prediction under future scenarios. In addition, further field studies and modelling work will be done at Suhm Creek basin to test the similarity and reproducibility of conceptual models developed for Scotty Creek basin. Activities for permafrost modelling will concentrate on field studies to better understand the energy dynamics of receding permafrost at the edges of treed plateaus. One example of this is sampling the subsurface permafrost composition using electrical resistivity imaging. As well, work will be completed to predict permafrost thaw using the northern ecosystem soil temperature (NEST) model (Zhang et al., 2006). Permafrost models are typically run at relatively coarse resolutions (e.g., 1000 km<sup>2</sup>), however, information generated from ongoing work (e.g., land cover distributions generated from remote sensing) will be leveraged to scale this model for application at finer spatial scales (e.g., 1 km<sup>2</sup>). Activities toward basin-scale hydrological prediction will include preparing CHRM and Raven hydrological models to simulate streamflow in Scotty Creek and Suhm Creek research basins. The accuracy of these models will be evaluated using instruments deployed throughout the basins, and adjustments to model parameters can be incorporated as necessary. Once it has been established that reasonable modelling accuracy has been achieved, these

models will be coupled with NEST to simulate future water resources scenarios according to hypothetical land cover changes.

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## References

- Baltzer, J.L., Veness, T., Chasmer, L.E., Sniderhan, A. and Quinton W.L. (2014): Forests on thawing permafrost: fragmentation, edge effects, and net forest loss; *Global Change Biology*, v. 20, no. 3, p. 824–834, doi:10.1111/gcb.12349
- Beilman, D.W. and Robinson, S.D. (2003): Peatland permafrost thaw and landform type along a climate gradient; *in* Proceedings of the Eighth International Conference on Permafrost, M. Phillips, S.M. Springman and L.U. Arenson (ed.), Zurich, Switzerland, July 21–25, 2003, A.A. Balkema, v. 1, p. 61–65.
- Braverman, M. and Quinton, W.L. (2016): Hydrological impacts of seismic lines in the wetland-dominated zone of thawing, discontinuous permafrost, Northwest Territories, Canada; *Hydrological Processes*, v. 30, p. 2617–2627, doi:10.102/hyp.10695
- Chasmer, L., Hopkinson, C. and Quinton, W. (2010): Quantifying errors in plateau changes from optical data, Northwest Territories, Canada: 1947–2008; *Canadian Journal of Remote Sensing*, v. 36, no. S2, p. S211–S223, doi:10.5589/m10-058
- Chasmer, L., Hopkinson, C., Veness, T., Quinton, W. and Baltzer, J. (2014): A decision-tree classification for low-lying complex land cover types within the zone of discontinuous permafrost; *Remote Sensing of Environment*, v. 143, p. 73–84, doi:10.1016/j.rse.2013.12.016
- Coleman, K.A., Palmer, M.J., Korosi, J.B., Kokelj, S.V., Jackson, K., Hargan, K.E., Courtney Mustaphi, C.J., Thienpont, J.R., Kimpe, L.E., Blais, J.M., Pisaric, M.F.J. and Smol, J.P. (2015): Tracking the impacts of recent warming and thaw of permafrost peatlands on aquatic ecosystems: a multi-proxy approach using remote sensing and lake sediments; *Boreal Environment Research*, v. 20, no. 3, p. 363–377.
- Connon, R.F., Quinton, W.L., Craig, J.R. and Hayashi, M. (2014): Changing hydrologic connectivity due to permafrost thaw in the lower Liard River valley, NWT, Canada; *Hydrological Processes*, v. 28, no. 14, p. 4163–4178, doi:10.1002/hyp.10206
- GeoBase® (2014): National hydro network; Natural Resources Canada, URL <[http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/-\(urn:iso:series\)geobase-national-hydro-network-nhn?sort-field=relevance](http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/-(urn:iso:series)geobase-national-hydro-network-nhn?sort-field=relevance)> [October 2016].

- Government of the Northwest Territories (2008): NWT Climate Change Impacts and Adaptation Report, 2008; Northwest Territories, Environment and Natural Resources, 31 p., URL <[http://www.enr.gov.nt.ca/sites/default/files/reports/nwt\\_climate\\_change\\_impacts\\_and\\_adaptation\\_report.pdf](http://www.enr.gov.nt.ca/sites/default/files/reports/nwt_climate_change_impacts_and_adaptation_report.pdf)> [December 2016].
- Hayes, B.J.R. (2010): Horn River Basin aquifer characterization project, northeastern British Columbia (NTS 094I, J, O, P); progress report; *in* Geoscience BC Summary of Activities 2009, Geoscience BC, Report 2010-1, p. 245–248, URL <[http://www.geosciencebc.com/i/pdf/SummaryofActivities2009/SoA2009\\_Hayes.pdf](http://www.geosciencebc.com/i/pdf/SummaryofActivities2009/SoA2009_Hayes.pdf)> [November 2016].
- Heginbottom, J.A. and Radburn, L.K., compilers (1992): Permafrost and ground ice conditions of northwestern Canada; Geological Survey of Canada, Map 1691A, scale 1:1 000 000.
- Johnson, E. (2010): Conceptual water model for the Horn River Basin, northeast British Columbia (parts of NTS 094I, J, O, P); *in* Geoscience Reports 2010, BC Ministry of Energy, Mines and Petroleum Resources, p. 99–121.
- Lee, P. and Boutin, S. (2006): Persistent and developmental transition in wide seismic lines in the western boreal plains of Canada; *Journal of Environmental Management*, v. 78, no. 3, p. 240–250, doi:10.1016/j.jenvman.2005.03.016
- Patankar, R., Quinton, W.L., Hayashi, M. and Baltzer, J.L. (2015): Sap flow responses to seasonal thaw and permafrost degradation in a subarctic boreal peatland; *Trees – Structure and Function*, v. 29, no. 1, p. 129–142, doi:10.1007/s00468-014-1097-8
- Pomeroy, J.W., Gray, D.M., Brown, T., Hedstrom, N.R., Quinton, W.L., Granger, R.J. and Carey, S.K. (2007): The cold regions hydrological model: a platform for basing process representation and model structure on physical evidence; *Hydrological Processes*, v. 21, no. 19, p. 2650–2667, doi:10.1002/hyp.6787
- Quinton, W.L. and Baltzer, J.L. (2013a): Changing surface water systems in the discontinuous permafrost zone: implications for streamflow; *in* Cold and Mountain Region Hydrological Systems Under Climate Change: Towards Improved Projections, Proceedings of H02, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013, International Association of Hydrological Sciences, Publication 360, p. 85–92.
- Quinton, W.L. and Baltzer, J.L. (2013b): The active-layer hydrology of a peat plateau with thawing permafrost (Scotty Creek, Canada); *Hydrogeology Journal*, v. 21, no. 1, p. 201–220, doi:10.1007/s10040-012-0935-2
- Quinton, W.L., Adams, J.R., Baltzer, J.L., Berg, A.A., Craig, J.R. and Johnson, E. (2016): Permafrost ecosystems in transition: understanding and predicting hydrological and ecological change in the southern Taiga Plains, northeastern British Columbia and southwestern Northwest Territories; *in* Geoscience BC Summary of Activities 2015, Geoscience BC, Report 2016-1, p. 89–94, URL <[http://www.geosciencebc.com/i/pdf/SummaryofActivities2015/SoA2015\\_Quinton.pdf](http://www.geosciencebc.com/i/pdf/SummaryofActivities2015/SoA2015_Quinton.pdf)> [November 2016].
- Quinton, W.L., Hayashi, M. and Chasmer, L.E. (2009): Peatland hydrology of discontinuous permafrost in the Northwest Territories: overview and synthesis; *Canadian Water Resources Journal*. v. 34, no. 4, p. 311–328.
- Quinton, W.L., Hayashi, M. and Chasmer, L.E. (2011): Permafrost-thaw-induced land-cover change in the Canadian subarctic: implications for water resources; *Hydrological Processes (Scientific Briefing)*, v. 25, no. 1, p. 152–158, doi:10.1002/hyp.7894
- Quinton, W.L., Hayashi, M. and Pietroniro, A. (2003): Connectivity and storage functions of channel fens and flat bogs in northern basins; *Hydrological Processes*, v. 17, no. 18, p. 3665–3684, doi:10.1002/hyp.1369
- St. Jacques, J.M. and Sauchyn, D.J. (2009): Increasing winter base flow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada; *Geophysical Research Letters*, v. 36, no. L01401, doi:10.1029/2008GL035822
- The Raven Development Team (2016): Raven, version 2.6; modelling framework, University of Waterloo, <<http://www.civil.uwaterloo.ca/jrcraig/Raven/Main.html>> [May 2016].
- Williams, T.W. and Quinton, W.L. (2013): Modelling incoming radiation on a linear disturbance and its impact on the ground thermal regime in discontinuous permafrost; *Hydrological Processes*, v. 27, no. 13, p. 1854–1865, doi:10.1002/hyp.9792
- Williams, T.W., Quinton, W.L. and Baltzer, J.L. (2013): Linear disturbances on discontinuous permafrost: implications for thaw-induced changes to land cover and drainage patterns; *Environmental Research Letters*, v. 8, no. 025006, p. 1–12, doi:10.1088/1748-9326/8/2/025006
- Wright, N., Hayashi, M. and Quinton, W.L. (2009): Spatial and temporal variations in active-layer thawing and their implication on runoff generation; *Water Resources Research*, v. 45, no. W05414, doi:10.1029/2008WR006880
- Zhang, Y., Chen, W. and Riseborough, D.W. (2006): Temporal and spatial changes of permafrost in Canada since the end of the Little Ice Age; *Journal of Geophysical Research-Atmospheres*, v. 111, no. D22103, doi:10.1029/2006JD007284

