Permafrost Ecosystems in Transition: Understanding and Predicting Hydrological and Ecological Change in the Southern Taiga Plains, Northeastern British Columbia and Southwestern Northwest Territories

W.L. Quinton, Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, ON, wquinton@wlu.ca

J.R. Adams, Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, ON

J.L. Baltzer, Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, ON

A.A. Berg, Department of Geography, University of Guelph, ON

J.R. Craig, Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, ON

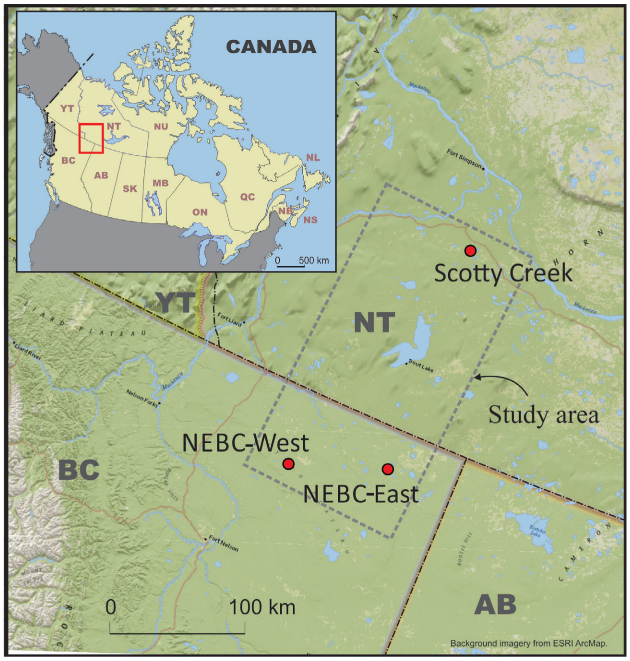
E. Johnson, Northeast Water Strategy, Government of British Columbia, Victoria, BC

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.

Introduction

The southern Taiga Plains ecoregion is one of the most rapidly warming regions on Earth, and is experiencing unprecedented rates of industrial expansion and related human disturbance. The permafrost in this region is relatively warm (e.g., between –1 and 0°C), thin and discontinuous. As a result, permafrost thaw is widespread and often leads to the transformation of forested permafrost terrains to permafrost-free, treeless wetlands. Such land-cover change, induced by permafrost thaw, has the potential to disrupt the hydrological cycle. Despite the demonstrated pan-arctic occurrence of this effect, the hydrological implications of this land-cover transformation remain poorly understood. As a result, there is an urgent need for an improved understanding of, and ability to predict, permafrost thaw and its hydrological consequences.

This paper describes the Consortium for Permafrost Ecosystems in Transition (CPET)—a new project that arose in direct response to these challenges. The CPET will develop and mobilize new knowledge on permafrost-thaw–induced land-cover change and the resulting hydrological and ecological impacts, and will use this new knowledge to develop a new suite of predictive hydrological modelling tools. Field measurements will concentrate on observatories located on an approximately 170 km long south-to-north transect that extends over the peatland-dominated southern fringe of discontinuous permafrost (Figure 1). This transect is ideally suited for the study of permafrost-thaw–induced changes to ecosystems and the resulting impacts on surface hydrology, since it covers a wide range of permafrost ecosystem characteristics along a climate gradient. Improved knowledge and predictive capacity of permafrost thaw patterns, rates, impacts and feedbacks will improve water planning, management and security by reducing the uncertainty of the future availability of freshwater, and enable better mitigation strategies to offset negative impacts.



Background imagery from ESRI ArcMap.

Figure 1: The Consortium for Permafrost Ecosystems in Transition (CPET) project transect extending in a north-south direction over the southern margin of discontinuous permafrost, northeastern British Columbia and southwestern Northwest Territories.

Keywords: *permafrost, environmental change, Taiga Plains*

This publication is also available, free of charge, as colour digital files in Adobe Acrobat® PDF format from the Geoscience BC website: http://www.geosciencebc.com/s/DataReleases.asp.

Background

In recent decades, the Taiga Plains ecoregion in northwestern Canada has become one of the most rapidly warming regions on Earth (Jorgenson et al., 2010). This warming is most pronounced in the southern Taiga Plains, including northeastern British Columbia (NEBC) and the adjacent southwestern Northwest Territories (NWT). There is mounting evidence that this warming is affecting the water cycle throughout the Taiga Plains. For example, the frequency of mid-winter melt events has increased (Semmens et al., 2013), end-of-winter snow melt occurs earlier (Francis and Vavrus, 2012) and key variables, such as snowpack depth (Cohen et al., 2014), snow cover extent (Derksen and Brown, 2012), surface water storage (Kurylyk et al., 2014a), groundwater flows (Bense et al., 2012) and seasonal precipitation patterns (Intergovernmental Panel on Climate Change, 2013), have deviated from long-term means. These changes are reflected in basin hydrographs throughout the Taiga Plains, where runoff in streams and rivers has steadily risen since the mid-1990s (St. Jacques and Sauchyn, 2009).

The current understanding of water flow and storage processes in wetland-dominated, discontinuous permafrost terrains, and how climate warming and the resulting ecological changes and feedbacks affect such processes, cannot explain this rise in flows, nor is it sufficient to predict future flows. Rising flows from subarctic rivers are often attributed to reactivation of groundwater systems (e.g., St. Jacques and Sauchyn, 2009), but the very low hydraulic conductivity of the glacial sediments of the border region, precludes appreciable groundwater input. Permafrost-thaw–induced changes to basin flow and storage processes offer a more plausible explanation for rising flows from rivers and streams in this region (Quinton et al., 2011; Connon et al., 2014).

Permafrost thaw is one of the most important and dramatic manifestations of climate warming (Rowland et al., 2010) in the Taiga Plains, yet its influence on runoff and streamflow is unclear. The southern Taiga Plains contain the southern fringe of permafrost (Kwong and Gan, 1994), where ice-rich permafrost, in the form of tree-covered peat plateaus, occurs as islands within a wetland-dominated, treeless, permafrost-free terrain of flat bogs, channel fens and other wetlands (Robinson, 2002). Because the permafrost underlying peat plateaus is relatively warm and thin (<10 m), less energy is required for permafrost thaw in this region than at higher latitudes, and as a result, the highest rates of permafrost thaw are found within the southern fringe (Camill, 2005). This permafrost is discontinuous and, therefore, its thaw is driven not only by vertical heat flows from the ground surface (Zhang et al., 2003), but also by horizontal heat conduction and advection from the permafrost margins (McClymont et al., 2013). As permafrost thaws, the overlying ground surface subsides and is engulfed by surrounding wetlands (Jorgenson and Osterkamp, 2005). This process gradually transforms permafrost terrains with forests into treeless, permafrost-free wetlands. Between 30 and 65% of the permafrost in the fringe zone has degraded or disappeared over the last 100–150 yr (Beilman and Robinson, 2003), with concomitant increases in wetland coverage (Quinton et al., 2011), and with forest-to-wetland conversion rates increasing in recent decades (Patankar et al., 2015).

Given that permafrost exerts a primary control on surface (Woo, 1986) and subsurface (Kurylyk et al., 2014a, b) hydrological processes, its disappearance has profound implications to the overall water cycle, including runoff, from local (Quinton and Baltzer, 2013) to regional (Rowland et al., 2010) scales. Rapid climate warming at high latitudes is projected to continue (Intergovernmental Panel on Climate Change, 2013) and model simulations suggest that this warming will produce greater discharge from drainage basins through the intensification (i.e., increased flow rates) of the hydrological cycle (Rawlins et al., 2013). It is also projected that accelerated permafrost thaw (Schaefer et al., 2011; Lawrence et al., 2012) may lead to the disappearance of permafrost throughout much of the southern fringe (Delisle, 2007; Zhang et al., 2008) over the next half century. However, simulations of permafrost loss are largely one-dimensional, run on large (e.g., 0.5 by 0.5°C) grids, and do not consider the co-occurrence of permafrost and nonpermafrost landscapes. The simulations do not explicitly account for the effects of subgrid processes, such as the lateral conductive and advective heat transfer between adjacent permafrost and permafrost-free terrains. Recent advances have enabled the modelling of discontinuous permafrost thaw using new three-dimensional numerical simulations of subsurface mass and energy transport. These simulations include freeze-thaw processes (e.g., Endrizzi et al., 2014; Kurylyk et al., 2014a,b) coupled to land-surface models (e.g., Zhang et al., 2003) and driven by general circulation model (GCM) output or higher resolution regional climate models (RCMs) following statistical downscaling (e.g., Wilby and Dawson, 2013) and bias correction (e.g., Bordoy and Burlando, 2013). These developments offer an important new opportunity to combine detailed field-based process studies with numerical modelling in order to improve the understanding of and ability to predict basin hydrographs that account for permafrost thaw and the resulting land-cover changes.

In the NEBC–NWT border region (hereafter border region), climate-warming–induced changes are exacerbated by unprecedented rates of industrial expansion. New roads and highways, pipelines, seismic lines, airstrips, drill pads and other infrastructure have the potential to profoundly affect permafrost, ecosystems and the hydrological cycle at local scales. Knowledge of permafrost thaw impacts are important to the petroleum industry since permafrost thaw greatly increases infrastructure construction and maintenance costs by causing pipeline ruptures, pad instabilities, foundation cracks from subsidence and the need for road resurfacing. Activities such as drilling wells and creating borrow pits, water storage ponds and linear features (e.g., winter roads, seismic lines, pipelines) all increase thaw rates by disturbing the insulating surface layer. Permafrost thaw and the resulting land-cover changes add uncertainty to the future availability of freshwater in the region. Industry requires both improved capacity to predict future water supplies and mitigation strategies to reduce the costs associated with industrial expansion in areas of permafrost.

Permafrost thaw is also of concern to local communities, including First Nations, especially with regard to its impact on the long-term health of water resources and natural ecosystems. In particular, unconventional gas extraction by hydraulic fracturing (fracking) has increased dramatically in the border region in recent years. Since hydraulic fracturing requires large volumes of water, industrial water use has also increased rapidly and is raising pressures on ecosystems and water supplies. However, the current lack of knowledge and predictive capacity of the rates, patterns, impacts and ecosystem feedbacks of permafrost thaw prevents communities from rigorous, science-based decision making on water resource and ecosystem planning and management, water and land permit approval and environmental impact assessment.

Both industry and governments acknowledge the lack of data on water resources and hydrology in the border region, and that water management in this region lacks sufficient information on permafrost thaw impacts. In response, the authors proposed CPET, a three-year (2015–2018) regional consortium of industry, provincial, territorial and federal government agencies, non-governmental organizations (NGOs), First Nations and other communities and stakeholders who will collaborate to improve the understanding of and ability to predict the impacts of permafrost thaw on shared water resources. The consortium approach is keenly supported by all participants and is fundamental to this project. The CPET was conceived from discussion with the Horn River Basin Producers Group (HRPG), Petroleum Technology Alliance of Canada, Fort Nelson First Nation, Liidlii Kue First Nation, BC Ministry of Forests, Lands and Natural Resource Operations, Geoscience BC, NWT Department of Environment and Natural Resources and the Water Survey of Canada. By contributing knowledge on permafrost thaw impacts to the implementation of both the BC Water Sustainability Act and NWT Water Stewardship Strategy, CPET will improve the scientific basis of the framework within which all water users of the border region will manage their shared resource, and will reduce the uncertainty of water futures by putting into the hands of trained end-users, customized science-based tools that will increase their predictive capacity.

CPET Research Direction

The CPET has five specific objectives:

1) Map the changing spatial distribution of permafrost, wetland and forest coverage over the past 60 years using aerial photography, satellite and light detection and ranging (LiDAR) images.
2) Conduct field studies for different ground thaw and moisture conditions 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.
3) 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.
4) 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.
5) Use information generated from the improved hydrological models (objective 3) and the permafrost model (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.

Study Sites

The CPET field studies will focus on three study sites (Table 1). Sites NEBC-East and Scotty Creek are the end-members of a 170 km long north-south transect through the fringe zone over which the wetland to forest ratio, permafrost concentration, climate and eco-hydrology vary. Site

Table 1: Location information for three study sites, northeastern British Columbia and southwestern Northwest Territories.

Site ID	Latitude	Longitude	Location	Area
NEBC-West	59° 29.056' N	122° 16.105' W	4.5 km east of Two-Island Lake	Horn River Basin, BC
NEBC-East	59° 42.460' N	120° 53.760' W	6 km west of July Lake	Cordova region, BC
Scotty Creek	61° 18.207' N	121° 17.628' W	50 km south of Fort Simpson	NWT

NEBC-West is wetland-dominated, with standing water and small lakes, but with greater topographic variation, greater variety of tree species and more mineral soil. The 1981–2010 climate normals indicate that Fort Simpson and Fort Nelson (located just south of the study area) have dry continental climates with short, dry summers and long, cold winters. Fort Simpson has an average annual air temperature of –2.8°C, and receives 388 mm of precipitation annually, of which 38% is snow (Environment Canada, 2013). Fort Nelson has an average annual air temperature of –0.4°C, and receives 452 mm of precipitation annually, of which 31% is snow (Environment Canada, 2013). The landscape at both Scotty Creek and NEBC-East are dominated by discontinuous permafrost (Heginbottom, 2000) and plateau–bog complexes, typical of the southern fringe of discontinuous permafrost. Both NEBC-East and Scotty Creek have experienced rapid and widespread permafrost thaw in recent decades.

Previous Work and Progress to Date

Recent work by CPET and others in the wetland-dominated, southern fringe of discontinuous permafrost or fringe zone (Kwong and Gan, 1994), has demonstrated that a) major land-cover types have contrasting hydrological functions, b) the relative proportions and spatial arrangement of these land-cover types is changing due to climate warming, and c) this warming-induced land-cover change is changing the water balance of drainage basins.

Contrasting Hydrological Functions

Ice-rich permafrost in the form of tree-covered peat plateaus dominates much of the fringe zone, where plateaus occur as forested permafrost islands within a wetland terrain of flat bogs and channel fens. The contrasting biophysical properties of these peatland types, gives each a specific role in the water cycle. Plateaus have a limited capacity to store water, a relatively large snowmelt water supply and an ability to direct excess water into adjacent wetlands (Wright et al., 2009). They have been found to function primarily as runoff generators, with runoff occurring predominately through the thawed, saturated layer between the water table and the relatively impermeable frost table below. Bogs are entirely surrounded by raised permafrost and are therefore unable to exchange surface or near-surface water with the basin drainage network. However, recent field studies at Scotty Creek, NWT, found that certain bogs can produce runoff, specifically, cascade bogs and open bogs. A cascade bog is one bog that belongs to a series of bogs connected by ephemeral channels. During periods of high moisture supply and/or limited ground thaw, such bogs cascade water through the series and into a fen. An open bog is one where the permafrost that once separated it from an adjacent fen has since thawed so that the bog is now open (i.e., connected) to the fen. This process of bog capture, as described in Connon et al. (2014), enables surface and near-surface flow between fens and open bogs during wet periods. Channel fens collect water from surrounding peatlands and convey it laterally along their broad (~50–100 m wide), hydraulically rough channels to streams and rivers (Quinton et al., 2003).

Warming-Induced Land-Cover Changes

As permafrost thaws, peat plateau surfaces subside and are flooded by the adjacent bogs or fens (Jorgenson and Osterkamp, 2005), a process leading to loss of forest and expansion of wetlands. At the Scotty Creek location, the proportion of a 1 km^2 area underlain by permafrost decreased from 70 to 43% between 1947 and 2008 (Quinton et al., 2011) and, currently, the fragmentation of peat plateaus is accelerating thaw rates (Baltzer et al., 2014). Electrical resistivity imaging across the width of plateaus at Scotty Creek indicated that permafrost is on the order of 10 m thick with edges that are close to vertical making the transition from permafrost to non-permafrost terrain abrupt (McClymont et al., 2013). Permafrost thaw involves simultaneous recession of these vertical edges and thickening of the active layer (Quinton et al., 2011).

Changes to the Water Balance of Drainage Basins

At Scotty Creek, field observations and image analyses suggest that plateaus contain two distinct runoff source areas separated by a break in slope approximately 10 m inland from the fen–plateau edge. Primary runoff drains from the sloped edges of plateaus directly into the basin drainage network (i.e., a channel fen). Field measurements suggest that the entire primary area supplies runoff to fens throughout the thaw season. Secondary runoff enters fens through a bog or a bog cascade, where the degree of hydrological connection with fens varies seasonally. As such, secondary runoff is neither direct nor continuous. The rate of secondary runoff is greatest during periods of high moisture supply and minimal ground thaw, when the hydrological connection among the bogs of a cascade, and also between individual bogs and their contributing areas (i.e., bogsheds), is maximized. As the active layer thaws and drains, the contributing area shrinks and secondary runoff decreases. Large rain events can temporarily reverse this decrease.

In comparing historical images of Scotty Creek, a basin typical of the border region, numerous bogs that were isolated from the drainage network in 1977 had become connected to it by 2008. This bog capture process increases basin runoff by increasing the basin's runoff contributing area (Connon et al., 2014). Specifically, bog capture adds to the basin drainage network through a) runoff arising from direct precipitation falling onto the captured bog (i.e., bog drainage), and b) runoff from the captured bog's watershed (i.e., slope drainage). As captured bogs expand due to permafrost thaw at their margins, they merge into other bogs. This process increases both the bog and slope drainage contributions to fens.

Future Work

Scotty Creek and NEBC-East are the primary sites for ongoing process studies and model development. This work will be supported by well-developed field research infrastructure and extensive data archives (1999–present) at Scotty Creek and new data at NEBC-East. The transferability of processes and models will be tested at intervening drainage basins along the north-south transect. However, this transect does not include upland forests and some of the peatland types typical of the Horn River Basin, which has a greater topographic variation. For this reason, NEBC-West was established as a study site to explicitly examine the permafrost thaw impacts on hydrology and ecology of biophysical units not represented along the north-south transect.

Acknowledgments

This project is funded by Geoscience BC and a Natural Science and Engineering Research Council of Canada Collaborative Research and Development grant and through partnerships with Nexen (a CNOOC Limited company), Fort Nelson First Nation and the government of Northwest Territories. The authors are grateful for the editorial comments from two reviewers that improved the report.

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.), A.A. Balkema, July 21–25, 2003, Zurich, Switzerland, v. 1, p. 61–65.

Bense, V.F., Kooi, H., Ferguson, G. and Read, T. (2012): Permafrost degradation as a control on hydrogeological regime shifts in a warming climate; Journal of Geophysical Research, Earth Surface, v. 117, no. 03036, 18 p., doi:10.1029/2011JF002143

Bordoy, R. and Burlando, P. (2013): Bias correction of regional climate model simulations in a region of complex orography; Journal of Applied Meteorology and Climatology, v. 52, no. 1, p. 82–101, doi:10.1175/JAMC-D-11-0149.1

Camill, P. (2005): Permafrost thaw accelerates in boreal peatlands during late-20th century climate warming; Climatic Change, v. 68, no. 1–2, p. 135–152, doi:10.1007/s10584-005-4785-y

Cohen, J., Screen, J.A., Furtado, J.C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J. and Jones, J. (2014): Recent Arctic amplification and extreme mid-latitude weather; Nature Geoscience, v. 7, p. 627–637, doi:10.1038/NGEO2234

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

Delisle, G. (2007): Near-surface permafrost degradation: how severe during the 21st century?; Geophysical Research Letters, v. 34, no. L09503, 4 p., doi:10.1029/2007GL029323

Derksen, C. and Brown, R. (2012): Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections; Geophysical Research Letters, v. 39, no. L19504, 6 p., doi:10.1029/2012GL053387

Endrizzi, S., Gruber, S., Dall'Amico, M. and Rigon, R. (2014): GEOtop 2.0: simulating the combined energy and water balance at and below the land surface accounting for soil freezing, snow cover and terrain effects; Geoscientific Model Development, v. 7, no. 6, p. 2831–2857, doi:10.5194/gmd-7-2831-2014

Environment Canada (2013): Canadian climate normals; Environment Canada, URL <http://climate.weather.gc.ca/climate_normals/index_e.html> [December 2013].

Francis, J. and Vavrus, S. (2012): Evidence linking Arctic amplification to extreme weather in mid-latitudes; Geophysical Research Letters, v. 39, no. L06801, 5 p., doi:10.1029/2012GL051000

Heginbottom, J.A. (2000): Permafrost distribution and ground ice in surficial materials; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, L.D. Dyke and G.R. Brooks (ed.), Geological Survey of Canada, Bulletin 547, p. 31–39.

Intergovernmental Panel on Climate Change (2013): Summary for policymakers; *in* Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (ed.), Cambridge University Press, Cambridge, United Kingdom and New York, New York, 27 p.

Jorgenson, M.T. and Osterkamp, T.E. (2005): Response of boreal ecosystems to varying modes of permafrost degradation; Canadian Journal of Forest Research, v. 35, no. 9, p. 2100–2111, doi:10.1139/X05-153

Jorgenson, M.T., Romanovsky, V., Harden, J., Shur, Y., O'Donnell, J., Schuur, E., Kanevskiy, M. and Marchenko, S. (2010): Resilience and vulnerability of permafrost to climate change; Canadian Journal of Forest Research, v. 40, no. 7, p. 1219–1236, doi:10.1139/X10-060

Kurylyk, B., MacQuarrie, K. and McKenzie, J. (2014a): Climate change impacts on groundwater and soil temperatures in cold and temperate regions: implications, mathematical theory, and emerging simulation tools; Earth-Science Reviews, v. 138, p. 313–334, doi:10.1016/j.earscirev.2014.06.006

Kurylyk, B.L., McKenzie, J.M., MacQuarrie, K.T.B. and Voss, C.I. (2014b): Analytical solutions for benchmarking cold regions subsurface water flow and energy transport models: one-dimensional soil thaw with conduction and advection; Advances in Water Resources, v. 70, p. 172–184, doi:10.1016/j.advwatres.2014.05.005

Kwong, J.Y.T. and Gan, T.Y. (1994): Northward migration of permafrost along the Mackenzie Highway and climate warming; Climate Change, v. 26, no. 4, p. 399–419, doi:10.1007/BF01094404

Lawrence, D.M., Slater, A.G. and Swenson, S.C. (2012): Simulation of present-day and future permafrost and seasonally frozen ground conditions in CCSM4; Journal of Climate, v. 25, no. 7, p. 2207–2225, doi:10.1175/JCLI-D-11-00334.1

McClymont, A.F., Hayashi, M., Bentley, L.R. and Christensen, B.S. (2013): Geophysical imaging and thermal modelling of subsurface morphology and thaw evolution of discontinuous permafrost; Journal of Geophysical Research, Earth Surface, v. 118, no. 3, p. 1826–1837, doi:10.1002/jgrf.20114

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

Quinton, W.L. and Baltzer, J.L. (2013): 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., 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

Rawlins, M.A., Nicolsky, D.J., McDonald, K.C. and Romanovsky, V. (2013): Simulating soil freeze/thaw dynamics with an improved pan-Arctic water balance model; Journal of Advances in Modeling Earth Systems, v. 5, no. 4, p. 659–675, doi:10.1002/jame.20045

Robinson, S.D. (2002): Peatlands of the Mackenzie Valley: permafrost, fire, and carbon accumulation; *in* Long-Term Dynamics and Contemporary Carbon Budget of Northern Peatlands, Z.C. Yu, J.S. Bhatti and M.J. Apps (ed.), Proceedings of International Workshop on Carbon Dynamics of Forested Peatlands: Knowledge Gaps, Uncertainty and Modelling Approaches, March 23–24, 2001, Edmonton, Alberta, p. 21–24.

Rowland, J.C., Jones, C.E., Altmann, G., Bryan, R., Crosby, B.T., Hinzman, L.D., Kane, D.L., Lawrence, D.M., Mancino, A., Marsh, P., McNamara, J.P., Romanvosky, V.E., Toniolo, H., Travis, B.J., Tochim, E., Wilson, C.J. and Geernaert, G.L. (2010): Arctic landscapes in transition: responses to thawing permafrost; Eos, Transactions, American Geophysical Union, v. 91, no. 26, p. 229–236, doi:10.1029/2010EO260001

Schaefer, K., Zhang, T., Bruhwiler, L. and Barrett, A.P. (2011): Amount and timing of permafrost carbon release in response to climate warming; Tellus Series B, Chemical and Physical Meteorology, v. 63, no. 2, p. 165–180, doi:10.1111/j.1600-0889.2011.00527.x

Semmens, K., Ramage, J., Bartsch, A. and Liston, G. (2013): Early snowmelt events: detection, distribution, and significance in a major sub-arctic watershed; Environmental Research Letters, v. 8, no. 1, no. 0.14020, 11 p., doi:10.1088/1748-9326/8/1/014020

St. Jacques, J.M. and Sauchyn, D.J. (2009): Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada; Geophysical Research Letters, v. 36, no. L01401, 6 p., doi:10.1029/2008GL035822

Wilby, R.L. and Dawson, C.W. (2013): The statistical downscaling model: insights from one decade of application; International Journal of Climatology, v. 33, no. 7, p. 1707–1719, doi:10.1002/joc.3544

Woo, M.K. (1986): Permafrost hydrology in North America; Atmosphere-Ocean, v. 24, no. 3, p. 201–234, doi:10.1080/07055900.1986.9649248

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, 13 p., doi:10.1029/2008WR006880

Zhang, Y., Chen, W.J. and Cihlar, J. (2003): A process-based model for quantifying the impact of climate change on permafrost thermal regimes; Journal of Geophysical Research Atmospheres, v. 108, no. D22, 13 p., doi:10.1029/2002JD003355

Zhang, Y., Chen, W. and Riseborough, D.W. (2008): Transient projections of permafrost distribution in Canada during the 21st century under scenarios of climate change; Global and Planetary Change, v. 60, no. 3–4, p. 443–456, doi:0.1016/j.gloplacha.2007.05.003