A Synthesis of Three Decades of Eco-Hydrological Research at Scotty Creek, NWT, Canada

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Abstract. Scotty Creek, Northwest Territories (NWT), Canada, has been the focus of eco-hydrological research for nearly three decades. Over this period, field and modelling studies have generated new insights into the thermal and physical mechanisms governing the flux and storage of water in the wetland-dominated regions of discontinuous permafrost that characterizes much of the Canadian and circum-polar subarctic. Research at Scotty Creek has coincided with a period of unprecedented climate warming, permafrost thaw, and resulting land cover transformations including the expansion of wetland areas and loss of forests. This paper synthesizes field and modelling studies at Scotty Creek, and highlights the key insights of these studies on the major water flux and storage processes operating within and between the major land cover types. This paper also provides insights into the rate and pattern of the permafrost thaw-induced land cover change, and how such changes will affect the hydrology and water resources of the study region.

1 INTRODUCTION

The lower Liard River valley lies in the continental boreal and discontinuous permafrost regions (Hegginbottom and Radburn, 1992) of northwestern Canada, and is characterised by approximately 53,000 km^2 of flat, organic terrain with a high density of open water and peatlands (Aylsworth and Kettles, 2000). The high density of peatlands helps to preserve permafrost due to the large thermal offset created by a dry, insulating peat surface soil layer (Camill and Clark, 1998). The

occurrence of discontinuous permafrost in the lower Liard River valley and much of the southern Northwest Territories (NWT) is therefore largely confined to the areas of high peatland coverage, with the remaining land-cover being largely permafrost-free (Figure 1a). Although this region is known to have a dry continental climate with short, dry summers and long, cold winters (MSC, 2017), over recent decades its climate has warmed at a rate twice the global average (Cohen et al., 2014; Richter-Menge et al., 2017) and is one of the most rapidly warming on Earth (Vincent et al., 2015). There is growing evidence in the scientific literature (e.g. Hinzman et al., 2013; St. Jacques and Sauchyn, 2009; Walvoord and Kurylyk, 2016; Walvoord and Striegl, 2007) that this warming is altering hydrological flux and storage processes with potential long-term consequences for the region's water resources. The intensive and coordinated field and modelling studies that began at Scotty Creek in the lower Liard River valley in the mid-1990s have therefore coincided with a period of rapid warming and warming-induced environmental changes.

Scotty Creek, in addition to its neighbouring basins of Manners Creek, the Birch, Blackstone and Jean-Marie rivers, all drain peatland-dominated land covers with discontinuous permafrost that typify not just the lower Liard River valley, but also the southern Taiga Plains and Boreal Plains ecoregions of Canada, and much of the circumpolar subarctic. In the 1990s, these basins were the focus of research in support of the Mackenzie GEWEX (Global Energy and Water Exchange) Study (MAGS) which aimed to improve the understanding of and ability to predict the flux and storage of water within and from the major biophysical land cover types of the Mackenzie River basin (Woo, 2008). MAGS researchers in collaboration with government agencies expanded precipitation and stream gauging networks in the lower Liard River valley (Figure 2), where they also improved the understanding of the water sources and pathways giving rise to stream hydrographs (Gibson et al., 1993). This led to advancements in the ability to simulate the hydrological response of basins in this region (e.g. Pietroniro et al., 1996; Hamlin et al., 1998). These studies were focused mainly on isotope geochemistry, satellite remote sensing and the evaluation of the performance of an existing hydrological model (WATFLOOD) for simulation of basin runoff. As such, they involved relatively little field-based investigation of hydrological processes.

In 1999, the emphasis of hydrological research in the lower Liard River valley shifted toward field-intensive studies, and the headwater area of the 152 km² Scotty Creek basin (61°18'N; 121°18'W) located 50 km south of Fort Simpson, emerged as the focus of this work. In that year, the first multi-year instrumentation was installed at Scotty Creek for long-term monitoring of ground temperatures, soil moistures, water levels and precipitation. The Scotty Creek headwater area (hereafter "Scotty Creek") refers to the upper half of the basin (Figure 1b) that is underlain by discontinuous permafrost (Hegginbottom and Radburn, 1992) and blanketed with a continuous cover of peat. These characteristics are typical of the 'continental high boreal' wetland region (NWWG, 1988), where peat accumulations in the range of 2 m (McClymont et al., 2013) to 8 m (Braverman and Quinton, 2016) typically overlie a clay/silt-clay glacial till deposit of low permeability (Aylsworth and Kettles, 2000).

After more than 20 years, this paper recounts the history of hydrological and related permafrost studies at the Scotty Creek Research Station (see www.scottycreek.com), from its inception in the mid-1990s to the present time. Through this process it is shown how field-based studies formed the basis of new conceptual models, which in turn shaped the development of new mathematical models. This paper also explains how the field and modelling studies at Scotty Creek have contributed to

5   research programmes elsewhere, and generally to cold regions hydrology and related disciplines. The following discussion begins with a characterisation of the landscape and description of the hydrological functioning of its major components. The properties and hydrological functioning of the active (i.e. seasonally-frozen) layer are then discussed, which provides the background for the subsequent discussion on runoff generation. The hydrological impact of permafrost thaw induced land cover change is then considered. Finally, the hydrological impact of linear disturbances, the most widely occurring form of

10   direct human disturbance at Scotty, is discussed.

2 LANDSCAPE CHARACTERISATION AND FUNCTIONING

At the time that field studies began at Scotty Creek, the hydrological function of such low relief, peatland-dominated zones of discontinuous permafrost was poorly understood. This lack of understanding was problematic, in large part, because it prevented the development of physically-based hydrological models for reliable prediction of runoff from a terrain type that

15   dominates much of the Canadian subarctic. It was also problematic because this terrain is a critical contributor to the global carbon balance (Grosse et al., 2011; Schaefer et al., 2011). Initial ground-based and remote sensing studies (Quinton et al., 2003) indicated that Scotty Creek is dominated by forested peat plateaus that are underlain by permafrost and rise 1 to 2 m above permafrost-free, treeless wetlands in the form of collapse scars (referred to as "flat bogs" in earlier publications on Scotty Creek) and channel fens. The plateaus and collapse scars are arranged into complexes, with individual complexes

20   separated by channel fens. The National Wetlands Working Group (1988) described collapse scars as resulting from thermokarst erosion, a process that transforms peat plateaus into flat, low-lying, treeless and permafrost-free wetlands. Given that black spruce (*Picea mariana*) forests exist only on areas underlain by permafrost (i.e. peat plateaus), the extent of permafrost at Scotty Creek can be estimated from aerial or satellite images using forest cover as a proxy (Carpino, 2017). A later study by Chasmer et al. (2011) presented new remote sensing methods of estimating permafrost distribution, including

25   the use of light detection and ranging (LiDAR) techniques to precisely define permafrost plateau edges based on ground surface elevation. Cross-sections of permafrost bodies at Scotty Creek measured from electrical resistivity imaging indicate they are on the order of 10 m thick with near vertical sides (McClymont et al., 2013).

The contrasting biophysical characteristics of the three land cover types (peat plateaus, collapse scars, and fens) led to the

30   proposition that each has a specific function in the basin water balance (Quinton et al., 2003; Hayashi et al., 2004). Since peat plateaus rise above the surrounding wetlands, support a relatively deep snow cover, and have a limited capacity to store hydrological inputs, these were seen to function mainly as runoff generators. In contrast, because collapse scars were thought

to be entirely surrounded by the raised permafrost of the plateaus, water entering these wetlands was assumed to remain in storage until evaporated or displaced into the groundwater system. In this sense, the plateaus were seen as "*permafrost dams*". In a later paper, Quinton et al. (2009a) distinguished between collapse scars that occur within peat plateaus and are hydrologically-isolated from channel fens, and those that are situated between plateaus and have an open connection with

5 channel fens. Although isolated collapse scars are large in number, they account for less than 5% of the Scotty Creek catchment, while the area occupied by connected collapse scars is more than five times larger and roughly equivalent to the area occupied by channel fens (Quinton et al., 2009a). This conceptualisation of the form and hydrological functioning of collapse scar wetlands was modified again by Connon et al. (2015) who demonstrated that many of these features that were assumed to be hydrologically isolated, can form ephemeral connections with a fen (either directly or via another collapse

10 scar or series of them) during periods of high moisture supply, such as during the snowmelt runoff period. (A more detailed discussion on the development and hydrological functioning of such connections is presented below in the context of permafrost thaw). Water draining from plateaus into channel fens is conveyed downstream toward the basin outlet, as the primary function of these features is lateral flow conveyance along their broad, hydraulically-rough channels. The water level response to summer rainstorms measured at several nodes along the main drainage network at Scotty Creek showed

15 that the flood-wave velocity is controlled by channel fen slope and hydraulic roughness in a way consistent with the Manning formula, suggesting that a roughness-based algorithm might be useful for routing water at the basin scale (Hayashi et al., 2004).

The contrast between the mainly storage function of the bogs and the conveyance function of the channel fens, suggests that

20 the relative proportion of these two cover types in a basin would influence the volume and timing of the outflow hydrograph. To investigate this possibility, the runoff response of Scotty Creek and four neighbouring basins (Jean-Marie, Birch, Blackstone and Martin Rivers) was examined by Quinton et al. (2003) for the four year period 1997 to 2000 in relation to the relative proportions of peat plateau, bog and fen, and other biophysical characteristics. This study lent support to the proposition that channel fens are primarily water conveyers and collapse scars predominantly store water since it showed

25 that runoff was positively correlated with the percentage of the basin covered by channel fens, and negatively correlated with the percentage of the basin covered by collapse scars. Although that study led to a new conceptual understanding of the hydrological functions of the major terrain types, the hydrological interactions among these terrains remained poorly understood. However, the study by Hayashi et al. (2004) shed light on such interactions using isotope geochemical methods. Specifically, they showed that Goose Lake at the headwater of Scotty Creek had a strongly enriched isotopic composition,

30 but that the stream water composition was gradually depleted over the 14 km flow distance from Goose Lake to the Scotty Creek outlet. This indicated a continuous hydrological connection between Goose Lake and the basin outlet, and that over this distance lateral drainage from peat plateaus contributed isotopically light and chemically dilute water to channel fens. The authors also found that later in summer when water levels were relatively low, Goose Lake became hydrologically disconnected from the basin outlet.

Hayashi et al. (2004) considered the collapse scar wetlands to be hydrologically-isolated as described by Quinton et al. (2003) however they noted that such wetlands abutting fens without an intervening permafrost barrier could also contribute to a fen the water they received from precipitation or as runoff from their adjacent peat plateaus. Chemical and isotopic

5 analysis of surface and subsurface waters in the Scotty Creek basin indicated that snowmelt water contributed less than half of the basin discharge during the spring freshet, indicating that a large amount of water must be stored overwinter, presumably in the lakes, channel fens and their abutting bogs (Hayashi et al., 2004). The total amount of water stored over the winter in the basin was estimated to be 140 to 240 mm, which was comparable to the average annual basin discharge (149 mm). The average evapotranspiration estimated from chloride mass balance computations was 280 to 300 mm per year,

10 which was consistent with the value of 275 mm per year estimated from precipitation minus runoff. The results presented by Hayashi et al. (2004) are consistent with those of Gibson et al. (1993), who found that only 40 to 50% of peak runoff in Manners Creek was supplied by snowmelt.

Collectively, these studies helped to define the unique hydrological functions of the land cover types that predominate not

15 only at Scotty Creek, but throughout much of the peatland-dominated zone of discontinuous permafrost. These studies also illustrate the unique hydrological behaviour of sub-arctic peatlands compared with their counterparts in warmer climates. Much of this unique functioning is due to the juxtaposition of permafrost (plateau) and permafrost-free (wetland) land covers, and the profound hydrological impact of permafrost which gives the plateaus a higher topographic position and therefore causes drainage toward and impoundment within the collapse scar wetlands. As such, these wetlands strongly

20 control the rate and pattern of drainage from the plateau-collapse scar complexes into the intervening channel fens.

3 ACTIVE LAYER PROPERTIES AND FUNCTIONING

By characterising the hydrological functions of (Quinton et al., 2003) and interactions between (Hayashi et al., 2004) the major land cover types, a new conceptual framework for runoff generation in wetland-dominated terrain with discontinuous permafrost had emerged. Such a conceptual framework was an essential step toward the development of a hydrological

25 model for this terrain type. However, field studies at Scotty Creek also focused on smaller scale phenomena driven by the need to improve the process understanding and parameterisation of the physical, hydraulic and thermal properties of the peat blanketing the bogs, fens and plateaus. For example, Quinton and Gray (2001) showed that estimation of subsurface flow from organic-covered, permafrost terrain requires that the elevation and thickness of the saturated layer be known because the peat permeability can decrease by 2 to 3 orders of magnitude between the ground surface and 40 cm depth. Since the

30 saturated layer is perched on the relatively impermeable frost table, its elevation decreases and thickness increases as the ground thaws and the frost table lowers. As such, knowing the degree of thaw of the active layer (i.e. frost table depth) is critical to estimating the rate of subsurface runoff, as is proper characterization of peat hydraulic properties. This early work

by Quinton and Gray formed the conceptual basis of the numerical model developed and applied by Wright et al. (2009) to route subsurface drainage over the topographic surface of the frost table. This model is discussed in more detail below.

Quinton et al. (2000) reported that the total porosity decreases by only 10% between the ground surface and 35 cm depth, indicating that the water storage coefficient rapidly decreases with depth. The authors also reported that active porosity typically decreases from approximately 80% to <50% over the same depth range. Quinton and Hayashi (2004) reported that the drainable porosity (i.e. the pore volume of water removed when the water table is lowered) decreases from approximately 0.6 near the ground surface to 0.05 at 40 cm depth. These relatively low values, especially at depth, enable a rapid response of the water table to hydraulic inputs to the ground surface. This rapid response is enhanced by very high infiltration rates and the close proximity of the saturated zone to the ground surface. Laboratory drainage tests combined with microscopic image analyses indicate that with increasing depth, the proportion of small, closed and dead-end pores increases as does the water content for a given pressure, and that the peat maintains a residual volumetric moisture content of 15-20% (Quinton and Hayashi, 2004).

Progress was also made toward understanding the hydraulic properties of peat at the pore scale. For example, Quinton and Gray (2001) showed that the dimensionless coefficient C of the relationship between friction factor, f and Reynolds Number, N_R, (i.e. $f = C/N_R$) increased linearly with the depth to the middle of the saturated zone, d [L]. Since $C = 2D^2/k$, where D [L] is the geometric mean pore diameter of the material encountered by the saturated layer, and k [L^2] is the soil permeability, the relationship between C and d allows an approximation of the variation in permeability with depth (Quinton and Gray, 2001). In a later study, Quinton et al. (2008) focused on the saturated hydraulic conductivity, K [LT^{-1}], the product of k and $\rho g/\mu$, where ρ [ML^{-3}] is the density of water, g [LT^{-2}] is the gravitational acceleration, and μ [ML^{-1}T^{-1}] is the dynamic viscosity. Three independent measures of K were used to explore how its value varies with depth: tracer tests, constant-head well permeameter tests, and laboratory measurements of undisturbed samples. The conductivity profiles contained very high values (10-1000 m d^{-1}) within the top *ca.* 0.1 m where the peat is only lightly decomposed, a large reduction with increasing depth below the ground surface in the transition zone, and relatively low values in a narrow range (0.5-5 m d^{-1}) below *ca.* 0.2 m depth, where the peat is in an advanced state of decomposition. Digital image analysis of resin-impregnated peat samples showed that K is essentially controlled by pore hydraulic radius, which decreases with depth due to increasing compaction by overlying sediments. The Quinton et al. (2008) study benefitted from the work of Hayashi and Quinton (2004), which extended the applicability of the Guelph permeameter method to the soil conditions of Scotty Creek (i.e. relatively thin soil overlying impermeable permafrost) and produced a new set of shape factors determined by numerical simulation.

The research on the physical and hydraulic properties of peat also made use of innovative analytical laboratory methods. For example, high-resolution X-ray tomographic images were used to elucidate the volume and configuration of the pore network from both two and three dimensions for discrete ranges of soil water pressure typically observed at Scotty Creek.

The active porosities measured in 2D and 3D were very similar, and the volumetric moisture content measured using the tomographic images closely approximated the gravimetric measurements (Quinton et al., 2009b). This volume loss was accommodated by the thinning and disaggregation of moisture films, although as the sample lost moisture, the flow network maintained a relatively even spatial distribution. In related studies, Quinton et al. (2009b) and Rezanezhad et al. (2009; 2010) used X-ray Computed Tomography (CT) to visualize the pore structure of peat from a peatland-dominated zone of discontinuous permafrost at Scotty Creek. They found that the pore distribution in the near-surface sample of peat was dominated by a single, large highly connected and complex pore space which accounts for 94-99% of the total inter-particle pore volume. Analysis of the tomographic images also revealed that with increasing depth, the pore size and the degree of interconnection among pores decreased rapidly while the number of pores and the tortuousity of the pathways connecting them increased. In subsequent studies using tomographic images (Rezanezhad et al. 2012; 2016), the authors showed the complex dual-porosity nature of peat with active (or mobile) and inactive (or immobile) regions within the pores, which can be an important factor in water storage, flow, and solute migration.

Knowledge gained from the above studies on the physical and hydraulic properties of the peat mantling the plateaus was instrumental to understanding the hydraulic response of the landscape. However, it was also recognised through other studies at Scotty Creek that the flux of water is closely coupled to the flux of energy. For example, Quinton and Gray (2001) showed that since K decreases with depth, the average K of the saturated layer of peat decreases with time as the relatively impermeable frost table lowers through the active (i.e. seasonally-thawed) layer as it thaws. Quinton and Gray (2003) demonstrated a strong correlation between cumulative degree-day ground surface temperature and the fraction of the cumulative ground heat flux used to melt ice in the active layer, and suggested that the former could be used to estimate the frost table depth. Hayashi et al. (2007) developed a simple but effective heat-conduction model to simulate the downward movement of the impermeable frost table during thawing. Simulations were compared with the ground heat flux measured simultaneously using calorimetric, gradient, and flux-plate methods. The majority (86%) of incoming ground heat flux was used to melt the ice in the active layer. Simulated depths to the frost table during the 2003 to 2005 thaw seasons matched closely with observed data for two contrasting ground-cover types.

The depth to the frost table was shown to vary widely over short distances (Quinton and Gray, 2001), and as a result, so too does the topography of the frost table. Wright et al. (2009) used this premise to demonstrate that topographic variations of the relatively impermeable frost table control the rate and direction of subsurface flow, since the flow rate is a function of the depth-dependant value of K and the frost table slope angle, while the flow direction is governed by the direction of the sloping frost table. As such, the frost table topography includes areas of pooled water in frost table depressions and areas of preferential flow in frost table channels, although such features are often transient as the thaw season progresses and the frost table thaws differentially. Variations in soil moisture were found to be the dominant factor controlling depth to the frost table whereby wetter areas were associated with deeper frost tables and wetter years had greater average end of summer thaw

depths (Wright et al., 2009). A recent study at Scotty Creek on the hydrological impacts of wildfire (Ackley, 2018) demonstrates close connections among thermal, physical and hydraulic properties of the active layer. This work shows that relative to an adjacent non-burned control site, a low-severity fire in July of 2014 increased the bulk density and moisture retention for a given level of applied negative pressure, and decreased porosity and hydraulic conductivity. They also

5   demonstrated that the average end-of-season thaw depth increased while its spatial variability decreased. By reducing heterogeneities of the ground surface, the fire reduced the topographic variations of the underlying frost table, thereby reducing preferential flow and storage. Similarly, Gibson et al. (In press) examined active layer dynamics in the years to decades following fire events. The authors concluded that representative active layer depth increased by approximately 50% in the first decade after the fire, with convergence to the depth observed in unburned sites on the order of 20 years post-fire.

Previous research in northern regions adapted runoff generation concepts developed for temperate or other regions such as variable source area, transmissivity feedback, and fill-and-spill (e.g. Tromp-van Meerveld and McDonnell, 2006). However, based on the close coupling of energy to the hydrological cycle demonstrated at Scotty Creek, a new "energy-based" framework was developed for delineating runoff contributing areas for organic-covered, permafrost terrains (Wright et al.,

15   2009; Quinton and Carey, 2008). Spatial variations of aerodynamic energy and roughness height affect the end-of-winter spatial distribution of snow (Pomeroy et al., 2004), while spatial variations of radiant energy control the spatial distributions of snowmelt and ground thaw rates. The combined spatial pattern of aerodynamic (i.e. turbulent) and radiant energy control the topographic variations of the relatively impermeable frost table. The features of the frost table, such as local areas of preferential thaw corresponding to areas of preferential subsurface storage or flow, persist year-to-year.

The field studies of thaw rates and patterns described above were complemented by laboratory investigations on the interaction of peat with the frost table. For example, in 2007, four 0.6 m diameter, 0.75 m deep peat cores with 0.25 m surface vegetation were sampled from permafrost plateaus at Scotty Creek and transported to Western University (London, Ontario, Canada) where they were installed in a climate controlled chamber and instrumented with energy and mass flow

25   sensors. The temperature and moisture gradients in the chambers were set to values measured in the instrumented soil pits established in 2003 (Table 1). These laboratory experiments, along with coupled heat and water transport numerical modelling, evaluated the sensitivity of soil freezing / thawing to variations in soil temperature and moisture, snow-cover thickness, radiation regimes, and mitigation measures to reduce the impacts of disturbance. Nagare et al. (2012) provided insight into the field observed movement of frost tables upward during winter. Soil water movement towards the freezing

30   front was inferred from soil freezing curves, liquid water content time series and from the total water content of frozen core samples. A substantial amount of water, enough to raise the upper surface of frozen saturated soil within 0.15 m of the soil surface at the end of freezing period appeared to have moved upwards from the permafrost zone. Diffusion under moisture gradients and effects of temperature on soil matric potential appear to drive such movement (Kurylyk and Watanabe, 2013). Further climate chamber and numerical studies by Mohammed et al. (2017) quantified the effects of mulching and its ability

to limit permafrost thaw and alterations to the ground thermal regime. Overall, the thermal buffering ability of the mulch had beneficial effects on slowing thaw due to its low thermal conductivity, which decouples the subsurface from meteorological forcing and impedes heat conduction. Aside from the dry ground-0.1 m mulch scenario which did not have a positive effect on reducing ground thaw, thaw reduction ranged from 12 to 75%, with the wet ground-0.3 m mulch scenario achieving the

5   maximum thaw depth reduction. Results also suggested that mulching over aging disturbances, such as seismic lines where permafrost is very degraded, may have the potential to stabilize thaw or even regenerate permafrost (Mohammed et al., 2017).

These studies collectively advanced our understanding of the critical and unique hydrological phenomena of the active layer.

10   Much of this uniqueness is ascribed to the presence of discontinuous permafrost, seasonally frozen soil, and the distinctive thermal, physical and hydraulic properties of peat. The key contributions, addressed concurrently through field, laboratory, and modelling investigations, were the identification of energy as a driver of runoff, the recognition of the considerable role of the vertical variability of peat on hydrological response, and the role of the dynamic frost table topography on storing and shedding water from peat plateaus. These phenomenon have since been identified as important in other landscapes, including

15   Prairie (Hayashi et al., 1998; Hayashi et al., 2003; Fang et al., 2010), subalpine (Carey and Woo, 2001; Carey et al., 2012; Pomeroy et al., 2003), taiga shield (Guan et al., 2010; Spence et al., 2010), arctic tundra (Liljedahl et al., 2016), and other subarctic regions of Canada (Devito et al., 2017; Ferone and Devito, 2004), Alaska (Yoshikawa and Hinzman, 2003) and Siberia (Brutsaert and Hiyama, 2012).

4 RUNOFF FROM PEAT PLATEAUS

20   Given the emergence of the conceptual framework for runoff generation described above, researchers at Scotty Creek focused their initial efforts on peat plateaus since these features were considered to be runoff generators. Wright et al. (2008) used a water balance approach and the Dupuit-Forchheimer equation to quantify sub-surface runoff from a plateau at Scotty Creek and showed that 1) these two computations yielded similar results in both years (2004, 2005) of study, and 2) runoff accounted for approximately half of the moisture loss from the peat plateau, most of which occurred in response to snowmelt

25   inputs. The melt of ground ice was also a significant source of water during the study periods, which was largely detained in soil storage. Soil moisture conditions prior to soil freezing were a major factor controlling the volume of runoff from the hillslope. Subsurface drainage rates declined dramatically after the snowmelt runoff period, when the majority of water inputs went to soil storage and evapotranspiration. The minimal lag between rain events and subsurface runoff response in both years suggests that much of the runoff produced from rain events is rapidly transported to the adjacent wetlands.

Early studies at Scotty Creek reported that the frost table is typically at or near the ground surface by the end of winter, suggesting that at the onset of ground thaw, the active layer is saturated or nearly saturated with ice and a small amount of

unfrozen water (Quinton and Gray, 2001). Data from instrumented soil pits indicated that the unfrozen water content was ~15-20% (volumetric), roughly consistent with the residual moisture value reported by Quinton and Hayashi (2004). Considering that at the time of soil freezing in the autumn, the water table is often at a depth of 40 cm or more, a frost table location near the ground surface implies considerable over-winter moisture movement within the active layer. Analysis of

5 the soil cores removed from the ground in April, 2003, indicated that between freeze-up and late winter, the total (frozen and unfrozen) soil moisture increased throughout the active layer, and that this increase was greatest close to the ground surface. It was also found that the total soil moisture below 0.3 m depth was close to saturation. However, as the cumulative number of active layer thaw measurements at Scotty Creek increased throughout the decade, the assumption that the active layer is nearly or fully saturated by the end of winter was called into question. For example, Quinton and Baltzer (2013)

10 demonstrated that the observed rate of thaw was often greater than could be explained using numerical models and suggested incomplete freezing of the active layer during winter or the existence of a perennially-thawed layer (i.e. talik) that provides an additional source of heat for active layer thaw. Since that study was published, the widespread occurrence of taliks has been demonstrated below linear (i.e. seismic) disturbances (Braverman and Quinton, 2016), in peatland areas 10-20 years following the occurrence of wildfire (Gibson et al., In press) as well as below large areas of peat plateaus (Connon et al.,

15 2018).

The new knowledge on peat thermo-physical and hydraulic properties formed the basis of a quasi-3D, coupled heat and water transfer model presented by Wright et al. (2009) to simulate active layer thawing and runoff generation in a plateau. This new model known as *SFASH* (Simple Fill and Spill Hydrology), applied a unique variation of the fill-and-spill runoff

20 paradigm to plateau runoff, whereby water stored in topographic depressions of the frost table is released (i.e. 'spilled') once a storage threshold is exceeded by precipitation forcing, or by thaw-induced changes to the depression storage capacity. Differential ground thaw makes this variation on the fill-and-spill runoff paradigm far more dynamic.

While Wright et al. (2009) considered relatively small (25 m^2) study plots along the sloping edges of peat plateaus (a part of

25 plateaus designated as a *"primary runoff"* producing area in a later study by Connon et al., (2014)), Christensen (2014) simulated runoff processes over the entire area of peat plateaus. In doing so, the author modified the Northern Ecosystem Soil Temperature (NEST) model of Zhang et al. (2003) and used it to provide the surface boundary conditions for two- and three-dimensional subsurface heat and water transfer models to simulate the vertical and lateral thawing of permafrost (McClymont et al., 2013; Kurylyk et al., 2016). A relationship was developed between plateau geometries and runoff timing.

30 Using a dimensionless form of the Boussinesq equation, similar to *SFASH* model, it was shown that the runoff timing from plateaus is dependent on the height and depth of a plateau. Using this relationship, along with the hydraulic radius to approximate plateau radius, the runoff timing from irregularly shaped plateaus can be calculated. Future efforts developing a better averaging technique for hydraulic conductivity and a more appropriate equivalent radius approximation are required for application of these methods over an entire basin. By combining the equations for runoff timing from individual plateaus

developed in this study with a routing algorithm for moving runoff throughout the basin, the hydrological response of an aggregate of peat plateaus in the discontinuous permafrost zone could be determined.

New knowledge and numerical descriptions of active layer thermal (Hayashi et al., 2007; Kane et al., 2001), physical
5 (Quinton et al., 2008; Hayashi and Quinton, 2004) and hydraulic (Wright et al., 2008) properties and processes were also incorporated into the Cold Regions Hydrological Model (CRHM). For example, Quinton and Baltzer (2013) used CRHM to evaluate the impact of permafrost thaw induced plateau shrinkage and subsidence on plateau runoff production. Stone *et al.* (in prep.) applied CRHM to a larger spatial scale to evaluate the impact of permafrost loss in 0.45 km^2 sub-catchment on runoff from an adjacent channel fen.

In summary, the preceding studies found runoff from peat plateaus to be mostly in the shallow subsurface and controlled by antecedent moisture storage and melt of ground ice. The presence of local taliks influences this initial state, but in general, the local runoff process is now readily modeled via a number of techniques; challenges remain in determining how this local runoff process scales up to a basin the size of the Liard and what happens to this water once it runs off to adjacent fens and
15 bogs.

5 SCOTTY CREEK IN TRANSITION

The land cover at Scotty Creek is among the most rapidly changing on the planet (Camill, 2005; Osterkamp and Romanovsky, 1999). Over successive years, changes to the landscape, such as the expansion of wetlands and flooding of forests, were clearly evident and indicative of permafrost thaw. This led to an investigation into the rate and pattern of
20 permafrost loss using tree-cover loss as a proxy (Quinton et al., 2011), which showed that the proportion of a 1 km^2 area underlain by permafrost decreased from 55% to 43% between 1970 and 2008. Although aerial photographs older than 1970 are available (e.g. 1947), their quality is low, and as a result so too is the confidence in drawing conclusions from their analysis. However, climate data recorded at Fort Simpson indicate that rapid warming in the region did not commence until the early 1970s (Quinton et al., 2009a, Fig. 8a), and numerical simulations with the NEST model (Christensen, 2014)
25 suggested relatively stable permafrost until approximately 1980. A subsequent study demonstrated that thaw rates are accelerating due to fragmentation of the permafrost bodies (Baltzer et al., 2014). In the discontinuous permafrost zone, permafrost thaw involves simultaneous lateral recession of the near vertical sides (which can be significant) (McClymont et al., 2013) of a permafrost body, and lowering of its permafrost table.

30 Connon et al. (2018) demonstrated that the development of talik is a kind of "*tipping point*" that greatly accelerates the rate of permafrost thaw. Specifically, they found that the permafrost below areas with a talik thawed five times faster than areas without a talik, as the unfrozen talik prevents energy loss from the permafrost body to the atmosphere during the winter.

Similarly, Gibson et al. (In press) concluded that sites with high talik presence after wildfire exhibited high rates of lateral bog expansion. Connon et al. (2018) also identified the critical thaw depths associated with talik development. For example, in early April 2016, the depth of re-freeze was measured at 135 points along nine transects that have been monitored for thaw depth and soil moisture since 2011. It was found that the average re-freeze depth was 65 cm. The minimum re-freeze depth was 60 cm, and re-freeze never exceeded 80 cm. The same results were found in replicate measurements in April, 2017. These findings indicate that if the ground thaws to a depth of 60 cm, it may not refreeze in the following winter, and if summer thaw reaches or exceeds 80 cm, it can be assumed that it will not entirely refreeze. These findings of Connon et al. (2018) are supported by the long-term active layer monitoring at Scotty Creek. For example, Quinton et al. (2011) reported that the average end-of-summer thaw depth for a peat plateau at Scotty Creek for the period 1999 to 2004 was 0.58 m with little variation from year to year (SD = 0.04). However, following, 2004, the thaw depth increased by approximately 0.07 m yr^{-1} such that by 2017 the average end of summer thaw depth had increased to 1.5 m. The increase in vertical thaw after 2004 coincided with an increase in the rate of lateral shrinkage of the plateau on which the measurements were made. The introduction of a talik changes the suprapermafrost layer from a single layered (active layer) to a dual layered (active layer and talik) system. The establishment of a talik accelerates permafrost thaw because it reduces the loss of heat from the underlying permafrost during winter while introducing a second thawing front to the overlying active layer.

Just as permafrost thaw is changing the hydrological function of bogs by introducing new drainage channels that connect them, it is also changing the hydrological function of the plateaus by introducing a talik, a new flowpath that conveys water throughout the year. Although taliks may be hydrologically-isolated in depressions of the permafrost table, others taliks extend across plateaus hydrologically-connecting the wetlands on either side of it (Figure 3). In the case of the latter, if the permafrost table is lowered to below the elevation of the water table of the adjacent wetlands, then the plateau is no longer able to function effectively as a permafrost dam as water can be conducted over the permafrost table through the talik throughout the year. As such, taliks can introduce a new subsurface flow path, which in addition to the new surface pathways resulting from "bog capture", contributes to the increase in basin hydrological connectivity. This process may have been responsible for the observed greater summer runoff from Notawhoka Creek than from Scotty Creek, due to the increased ground thaw depths within the Notawhoka Creek catchment that developed following an extensive wildfire in 2014 (Burd et al., In review).

Using CRHM, Quinton and Baltzer (2013) found that runoff from a rapidly thawing plateau decreased by 47% over a nine year period (2002-2010). The primary cause of decreased runoff was due to a reduction in the surface area of the plateau (i.e. runoff contributing area). The decrease in plateau surface area results in a direct increase to the surface area of the receiving wetland. Therefore, the precipitation input that would have previously been delivered to that wetland via subsurface flow through the plateau, is now delivered to the wetland directly. Where the above study examined the impact of permafrost thaw on runoff from a single plateau, subsequent field studies considered larger spatial scales in order to improve the

understanding of permafrost thaw on the basin hydrograph. For example, Connon et al. (2014) investigated how permafrost thaw impacts the routing of moisture between wetlands and to the channel fen. This study found that as permafrost thaws, wetlands become more interconnected and are more capable of exchanging surface and subsurface waters, thereby increasing basin contributing area. The authors found that this increase in connectivity was the primary cause of observed increases in

5   basin streamflow between 1996 and 2012. Haynes et al. (In review) analysed the water levels recorded at Scotty Creek for the period 2003 to 2017, and demonstrated a consistent, year to year reduction in water storage in all wetlands except for those that are hydrologically isolated from the basin drainage network. The increasing hydrological connectivity of the Scotty Creek drainage basin therefore appears to be coinciding with dewatering of the basin wetlands (Figure 4). The authors also demonstrated that for the overlapping period of the discharge and water level records, the magnitude of wetland water

10   loss accounted for approximately 10% of the increased basin discharge when normalised by basin area (Figure 4), and that the increased basin discharge was largely driven by the expansion of the runoff contributing area through the permafrost thaw-induced process of bog capture.

The energy-driven runoff generation concept (Wright et al., 2009) described above provided the theoretical basis for a

15   conceptual model of preferential ground thaw and permafrost degradation proposed by Quinton et al. (2009). They suggested that canopy thinning due to disease, fire or other disturbance increases radiation loading to the ground surface, which leads to local thaw depressions toward which subsurface water drains. This process produces local areas of elevated soil moisture content with a concomitant increased bulk thermal conductivity. More thermal energy would then be transferred into the ground, further deepening and broadening the thaw depression, leading to surface saturation, loss of tree canopy, more

20   energy loading at the ground surface, and eventually through this sequence of positive feedbacks, lead to a local loss of permafrost. It is clear that the hydrological functioning of systems such as that at Scotty Creek are deceptively complex, likely much more so than they would be under colder continuous permafrost conditions or warmer permafrost-free conditions.

25   The recognition of on-going permafrost thaw and resulting land-cover change forced a reconsideration of the conceptual model of basin runoff earlier envisioned by Quinton et al. (2003) and Hayashi et al. (2004), which assumed that the plateaus and wetlands were static features. Rising flows from Scotty Creek and the gauged basins in the lower Liard River valley is often attributed to 'reactivation' of groundwater systems (St. Jacques and Sauchyn, 2009), however the low hydraulic conductivity of the glacial sediments and the minor winter-period flows of rivers in this region (<5% of annual flow)

30   suggests other causes (WSC, 2017). Permafrost thaw-induced change to basin flow and storage processes offers a more plausible explanation (Connon et al., 2014; Haynes et al., In review). In light of the new understanding of permafrost thaw, the analysis of how basin runoff varies with land cover type (Quinton et al., 2003) was expanded by Connon et al. (2014) for the period 1996 to 2012 and the results were re-evaluated in the context of the hydrological impacts of permafrost thaw-induced changes to the land cover. The concept of thawing permafrost resulting in a landscape with a higher percent cover of

bogs would suggest that basin storage is increasing. Connon et al. (2014) found that basin discharge was increasing at a rate disproportional to precipitation change (Figure 2), suggesting that basin water storage should be decreasing. It was therefore concluded that the hydrologic function of collapse scar wetlands was not correctly parameterised. Connon et al. (2014) also considered the hydrological impact of the thawing of permafrost barriers (i.e. peat plateaus) that separate bogs from channel

5 fens. This process the authors referred to as '*bog capture*' transforms internally drained bogs to 'open bogs' that are hydrologically connected to fens. Bog capture increases basin runoff by adding to it the runoff from direct precipitation onto captured bogs, and the runoff entering such bogs from their local contributing areas, termed "*bogsheds*" (Connon et al., 2015). As captured bogs expand due to permafrost thaw at their margins, they merge into other bogs, a process that further expands the basin runoff contributing area, and therefore basin runoff as well. Although Quinton et al. (2003) demonstrated

10 that greater bog coverage is associated with lower basin runoff, the hydrological function of captured bogs is more like that of channel fens as envisioned by Quinton et al. (2003) and should be parameterised as such. As shown in Connon et al. (2014), basins with a greater initial coverage of isolated bogs are likely to produce greater runoff as the process of bog capture manifests over the landscape. However, this also suggests that the increasing runoff trends (Figure 2) have an upper limit, as bog capture will decline as the number of remaining isolated bogs declines. Consequently, there is a diminishing

15 impact of bog capture on basin runoff as permafrost thaw progresses.

Connon et al. (2014) proposed dividing plateaus into primary and secondary runoff producing areas. The primary areas are the sloped margins of peat plateaus that drain directly and continuously into the basin drainage network (i.e. channel fens). The secondary areas deliver runoff to fens through a bog or a bog cascade whose degree of hydrological connection with a

20 fen varies seasonally as a function of the degree of soil thaw and moisture supply. For instance, a cascade is an ephemeral flow path that is activated only during periods of high moisture supply. The bog cascades allow for previously isolated wetlands to interconnect via drainage channels that cut through the intervening plateau. These toposequences ultimately drain into the channel fen network, where water is made available to the basin drainage network. The cascading wetlands operate in a manner similar to the 'fill-and-spill' principle, where wetlands are not capable of shedding water until their

25 storage capacity has been filled (Connon et al., 2015), similar to hydrological systems in the Prairie Potholes Region (Hayashi et al., 2016) and the Canadian Shield (Spence and Woo, 2003), though driven by a somewhat different phenomenon. Connon et al. (2015) also showed that the storage deficit of an individual wetland complex is highly dependent on the plateau:wetland ratio: wetlands with *more* plateaus yield considerably more runoff. Large wetlands with a low plateau:wetland ratio can act as 'gatekeepers' (see Phillips et al., 2011), preventing the transmission of water to downstream

30 wetlands. The plateau:wetland ratio of the entire toposequence can also have a substantial impact on total runoff as shown in Figure 5 which contrasts the runoff response of two adjacent wetland cascades.

Thermokarst bog development and permafrost aggradation has likely been cyclical in this region, with a return period for permafrost re-aggradation as short as 600 years after thaw (Zoltai, 1993). Analysis of peat cores from Scotty Creek found

that the collapse scar wetlands at Scotty formed at various times over the last 1250 years (Pelletier et al., 2017), while aerial image analysis has identified several such wetlands that have developed over the last half century (Gordon et al., 2016). Previous studies on such wetlands (e.g. Quinton et al., 2003; Connon et al., 2014) assumed relatively uniform characteristics among them. However, the collapse scar wetlands can and likely should be further sub-classified by geochemical function

5 and groundwater connection. Gordon et al. (2016) investigated the production of methylmercury (MeHg) along the same toposequence studied by Connon et al. (2015). The authors found that the lower three collapse scar wetlands were more appropriately described as "minerotrophic poor fens", due to the higher pH of their pore water, and presence of graminoids and sedges. Thawing permafrost leads to the expansion of both ombrotrophic and minerotrophic wetlands, and the percent cover of each of these wetland types will have implications on future water quality. Both ombrotrophic and minerotrophic

10 wetlands can exist in close proximity and in the same drainage cascade. Although both are devoid of permafrost, the ground surface of ombrotrophic wetlands is typically above the potentiometric surface of the local groundwater table, and therefore these wetlands recharge groundwater systems. By contrast, the minerotrophic wetlands occupy an elevation at or below the local potentiometric surface, where relatively small but consistent upward directed hydraulic gradients maintain groundwater discharge (Christensen, 2014; Gordon et al., 2016). Gordon et al. (2016) found significantly higher MeHg concentrations in

15 the minerotrophic wetlands than in the ombrotrophic wetlands of the same toposequence. Similar results are reported for wetlands in non-permafrost regions (e.g. Branfireun and Roulet, 2002; Mitchell et al., 2008), suggesting that minerotrophic wetlands may be 'hot spots' for MeHg production, a major toxin that has become more prevalent in the food chain in recent years, and is of major concern to northern communities (Laird et al., 2018; Reyes et al., 2017). Understanding the trajectory of permafrost thaw-induced land cover change, including the development of such hot spots, therefore has important

20 implications for water quality.

The effects of land-cover change from forested peat plateaus to treeless wetlands not only have a direct effect on the basin hydrology, but also affect the partitioning of energy. Chasmer and Hopkinson (2017) predict that by as early as 2044 the Scotty Creek basin could be devoid of near-surface permafrost. Using a hypothetical scenario of a complete wetland landscape, Helbig et al. (2016) calculated a regional near-surface cooling of 3-4°C at the end of winter resulting from the

25 increased albedo of the treeless landscape assuming that the resulting landscape resembled a current bog system. The net effect of this hypothetical landscape on snowmelt runoff is not yet understood. End of season snow water equivalent (SWE) is projected to be lower as the snowpack in channel fens is, on average 40% lower than the forests of the plateaus (Haughton, 2018). This is due to over-winter redistribution of the snowpack and wind-blown sublimation loss. The open forest canopy

30 does not intercept a considerable amount of snow but the presence of trees greatly reduces wind speed to retain significantly more snow than the channel fens (Haughton, 2018). The amount of snow in collapse scar wetlands is highly dependent on the fetch size. Haughton (2018) found that snowmelt at Scotty Creek is primarily driven by incoming shortwave radiation, and found that snowmelt in open areas (i.e. wetlands) occurs much earlier than in forested peat plateaus. In the subarctic Yukon River basin, Semmens et al. (2013) found that the onset of snowmelt is occurring earlier primarily due to higher

moisture availability for condensation and rain-on-snow events as opposed to increased temperatures. As plateaus transition into wetlands it is expected that localised cooling of near-surface air temperatures may prolong snowmelt but decreased snow cover, increased radiative loading, and higher moisture supply to the snowpack during spring will collectively accelerate the melt process. Due to high input volumes and restricted infiltration rates in frozen soil, most storage deficits in

5   the basin are satisfied during snowmelt, indicating that most flow paths are active and hydrological connectivity is highest. Therefore, in addition to changes in snowmelt timing, more meltwater is made available to the basin drainage network. Figure 6 presents a composite hydrograph for two 10 year periods (1976-1985 and 2006-2015) in the Jean Marie River basin, a watershed adjacent to Scotty Creek, with long term hydrometric data. This figure illustrates significant increases to basin runoff during the spring freshet where runoff ratios have doubled over the 40 year period.

Scotty Creek occupies a landscape in transition. The close dependence of hydrology upon the energy budget and the sensitivity of the permafrost to small perturbations in vegetative cover and radiative input, changes in the regional climate directly lead to changes in the landscape; slowly transitioning from a peatland-dominated to a wetland-dominated system. As shown above, this has profound hydrological implications but will also impact water quality and the regional carbon balance.

15   These changes can be further exacerbated by the presence of seismic lines and other human intervention.

6 LINEAR DISTURBANCES

Linear disturbances, including winter roads and seismic lines introduced to Scotty Creek between 1942 and 1985, present a case of preferential permafrost thaw worthy of study for two main reasons: 1) the wide occurrence of these features raises the question of their impact on local and basin runoff processes, and 2) new knowledge on how permafrost thaw beneath

20   disturbances affects hydrological processes can be applied throughout Scotty Creek and beyond. Linear disturbances are the most widely occurring types of anthropogenic disturbance at Scotty Creek. The density of such disturbances (i.e. total length divided by basin area) is approximately 7 times greater than the density of the drainage network of channel fens and open channels. Where the linear disturbances (i.e. winter roads, seismic lines) traverse plateaus, the tree canopy was felled and the permafrost has thawed producing a grid of linear, permafrost-free corridors, which allow isolated bogs to drain, and

25   hydrological connections among bogs, fens and plateaus to form. Williams and Quinton (2013) demonstrated that following a disturbance to the ground surface the primary driver of permafrost thaw is the elevated soil moisture content which increases the thermal conductivity of the peat allowing more energy to be transported to the thawing frost table or permafrost table. During the initial disturbance, the soil is compacted and the porosity is reduced. As a result, both soil moisture and bulk thermal conductivity increase, and permafrost thaw is initiated. Subsurface flows are then directed to the disturbance

30   due to the topographic depression in the permafrost table further increasing the soil moisture content and rate of ground thaw in the disturbance (Quinton et al., 2009a). Therefore, once permafrost along linear disturbances thaws, it is unlikely to regenerate (Williams et al., 2013). In an initial investigation of the effect of seismic lines on basin hydrology, Williams et al.

(2013) found that, similar to drainage through bog cascades, drainage through these features operates under the fill-and-spill principle providing water to the channel fen during periods of high moisture supply. This study also suggested that further thaw and subsidence along seismic lines may change their hydraulic behaviour to function more like channel fens.

5 To further investigate the impacts of linear disturbances on basin hydrology, a 195 m segment of a seismic line cut in 1985 was instrumented in 2012. The seismic line traverses a 90 m-wide plateau, connecting a channel fen on one side of the plateau to a flat bog on the other. The seismic line was instrumented with thermistors, pressure transducers (water level recorders), net radiometers, and snow depth sensors (Braverman and Quinton, 2016). Regular measurements of snow and thaw depth were made between 2012 and 2015 along the seismic line and on adjacent plateaus. Geophysical imaging was

10 also conducted to gain insights into how permafrost has degraded. Braverman and Quinton (2016) demonstrated that once thaw lowers the elevation of the permafrost table below the ground surface elevation of adjacent bogs and fens, the seismic line forms a hydrological connection between the two wetlands. This hydrological connection persists year-round as surface and subsurface water is directed laterally along the linear disturbance and can drain wetlands from which the linear disturbance cuts through. Nearly half (45%) of subsurface runoff in the seismic lines occurs in the winter months beneath the

15 seasonally frozen layer implying that in areas of thawing, discontinuous permafrost the landscape remains hydrologically active throughout the winter.

7 SUMMARY AND CONCLUSIONS

Research at Scotty Creek has greatly improved the understanding and numerical representation of the key physical, hydraulic and thermal properties of peat that not only blankets this study site, but also much of the Boreal, taiga and tundra land covers

20 throughout the circum-polar region. For each of the major peatland types of Scotty Creek, the water flow and storage processes have been identified and the hydrological function in relation to the basin water balance has been defined. We have also demonstrated how these functions are changing with permafrost thaw. Although several studies in various arctic and subarctic locations have suggested that permafrost thaw may cause stream flows to increase, they do not provide a mechanistic explanation of how permafrost thaw would have this affect. However, Scotty Creek researchers showed how the

25 gradual removal of the relatively impermeable permafrost substrate increases the lateral transfer and surface and near-surface flows, which greatly increases the proportion of the basin that is capable of generating runoff. This is an example of how the extensive data archive of over twenty years of permafrost and hydrometric monitoring greatly strengthens the process field studies at Scotty Creek. Because the dominant peatland types at Scotty Creek also predominate throughout much of the subarctic, the new scientific knowledge developed at Scotty Creek on the form and functioning has contributed significantly

30 to a wide range of scientific fields as indicated by the large number of references to studies conducted at Scotty Creek by researchers external to Scotty Creek. During the ongoing period of research at Scotty Creek, more than 60 indexed peer-reviewed articles have been published, which have collectively received nearly 1200 citations predominantly in the fields of

water resources, environmental sciences, meteorology and atmospheric sciences (Web of Science, 2018). For example, the dramatic changing of biophysical land cover types from forested peat plateaus to treeless wetlands demonstrated at Scotty Creek has since been found to occur in other northern regions following the methods used at Scotty (e.g. Chasmer et al. 2016). The increasing prevalence of taliks at Scotty Creek (Connon et al., 2018) has led other authors to investigate the

5   extent of taliks in other regions (e.g. Lamontagne-Hallé et al., In press), many of whom also report an increase in the number of active flowpaths, especially during the winter months when most hydrological processes were previously assumed to be dormant (Sjöberg et al., 2016; Walvoord et al., 2012). The rates and patterns of permafrost thaw documented at Scotty Creek has also informed studies examining the cycling and storage of solutes (e.g. Olefeldt et al., 2014, Korosi et al., 2015, Tank et al., 2012) and mercury (Korosi et al., 2015; Gordon et al., 2016) in the thawing landscape, as well as the cumulative impacts

10 of permafrost thaw on aquatic ecosystems (e.g. Burke et al., 2018; Coleman et al., 2015). The rapid rate of permafrost thaw reported at Scotty led to investigations on how permafrost thaw affects aqueous (e.g. Olefeldt et al., 2014) and atmospheric (e.g. Helbig et al., 2017a; 2017b) carbon fluxes both in the Taiga Plains eco-region, and in the larger circum-polar region (Olefeldt et al., 2016).

15 **Author Contributions**

All authors were involved in synthesizing the presented information and preparation of the manuscript.

Competing Interests

The authors declare that they have no conflict of interest.

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Table 1: Instrumentation at Scotty Creek Research Site

1996	Scotty Creek gauging station installed
1999	Old Camp (seasonal) established
	Installed: water level recorders, ground temperature sensors, hydrometric sensors
	Initial ground thaw surveys, snow surveys
2001	Instrumented (temperature, soil moisture) soil pits, wells, expanded hydrometric sensor arrays
2003	Climate Station (Plateau 1: degrading plateau, sparse canopy)
2004	Climate Stations (Bog 1: direct connection to channel fen; Fen 1: channel fen draining small lake; upgraded Plateau 1 station)
2006	Snow courses introduced for annual snow surveys
2007	Climate Station (Plateau 2: stable plateau, dense canopy)
2008	First Lake Camp (all-season) established
2009	Deep (10 m) thermistors installed
2010	10 m flux tower
2012	Goose Lake Camp (all-season) established
	18 m flux tower and complementary Bog flux station
	Initial instrumentation of seismic line: climate stations, deep thermistor profiles, experimental thermosyphons
2014	Climate Stations: Plateau 3 (stable plateau, sparse canopy), adjacent Burned Forest Station and Non-Burned Station
	All water level recorders anchored and logging year-round
2015	Climate Station (Fen 2: channel fen, large drainage lake)
2017	Boardwalks and Expansion of Goose Lake Station infrastructure
	NASA / ABoVE flights for remote sensing image acquisition over Scotty
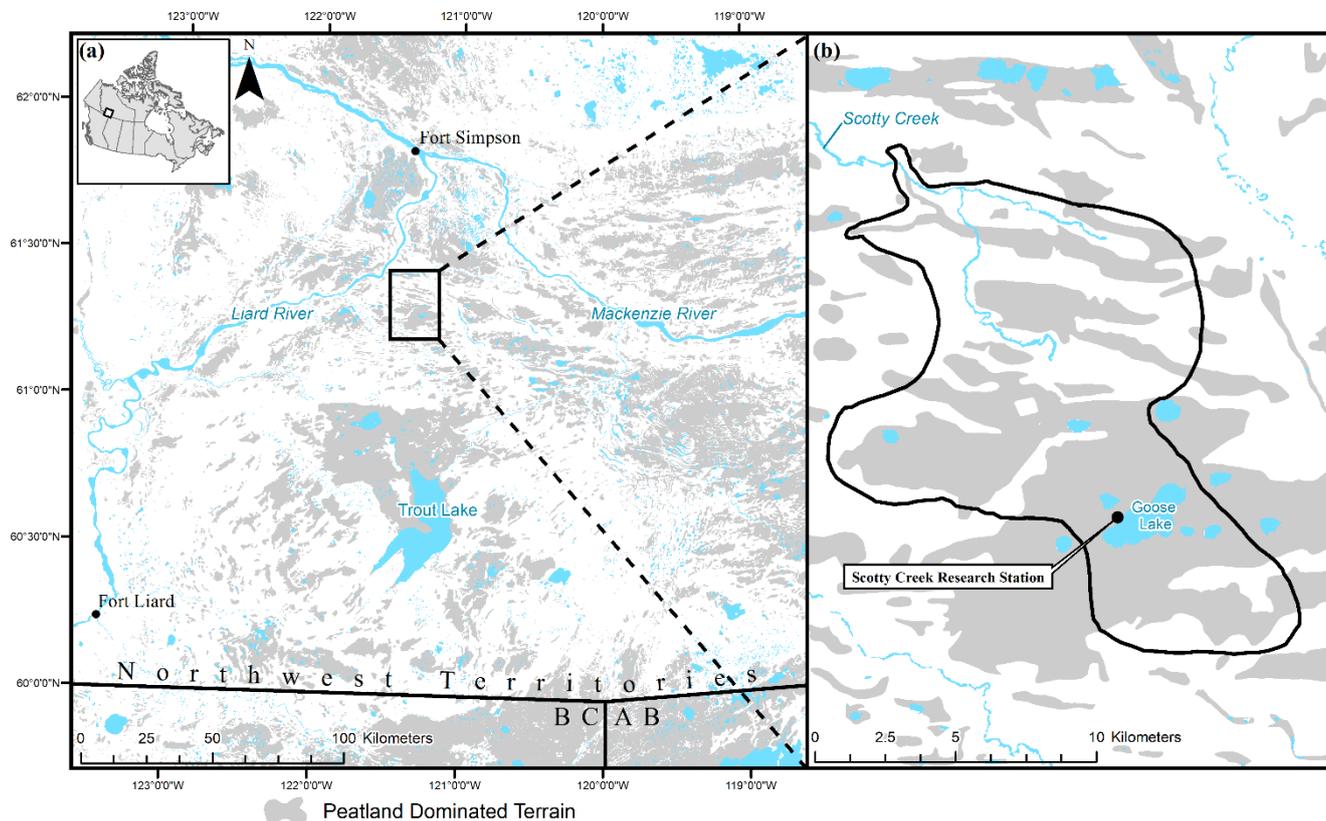
Figure 1: Distribution of wetland-dominated terrain containing discontinuous permafrost throughout the southern NWT (a), including the Scotty Creek drainage basin (b).
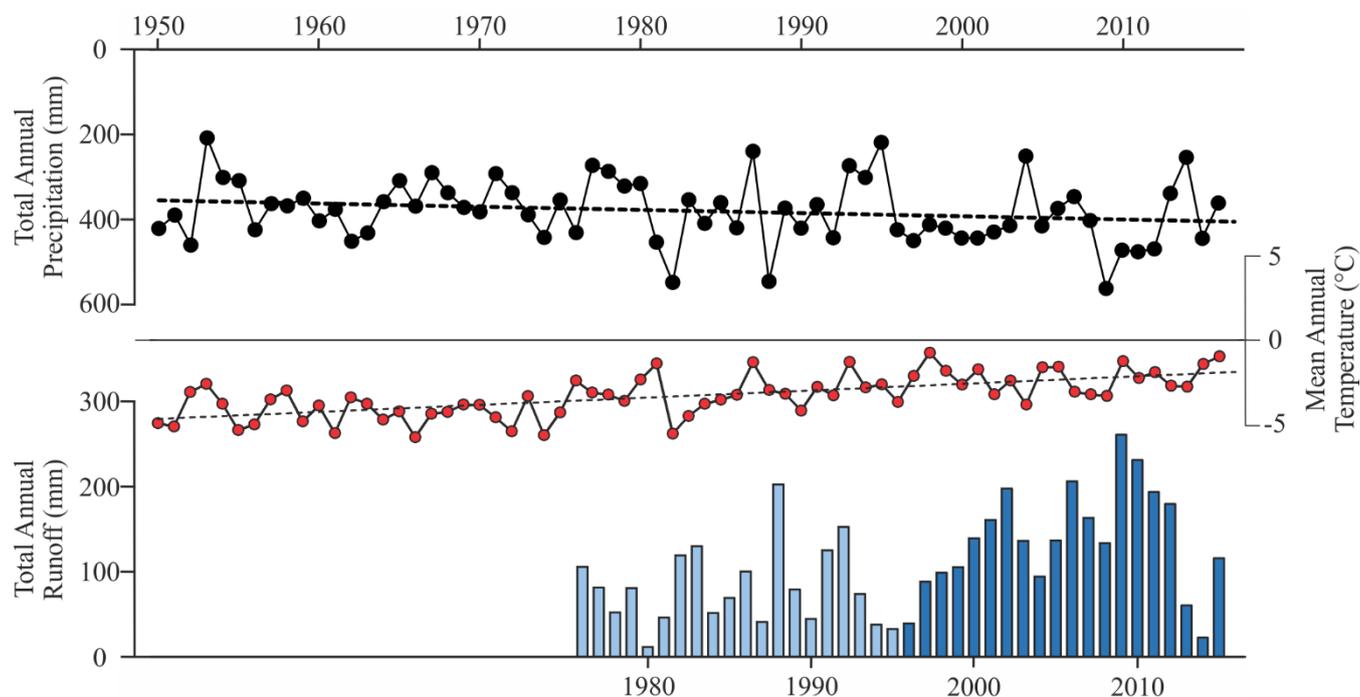
Figure 2: Historical precipitation, temperature and runoff at Scotty. Runoff after 1995 was measured directly by the Water Survey of Canada, and runoff prior to 1995 was estimated by interpolation from Water Survey of Canada data at an adjacent watershed (Jean-Marie River). Precipitation and air temperature were measured at the Fort Simpson A Climate Station by
5 **Environment Canada.**

Isolated Talik   **Connected Talik**
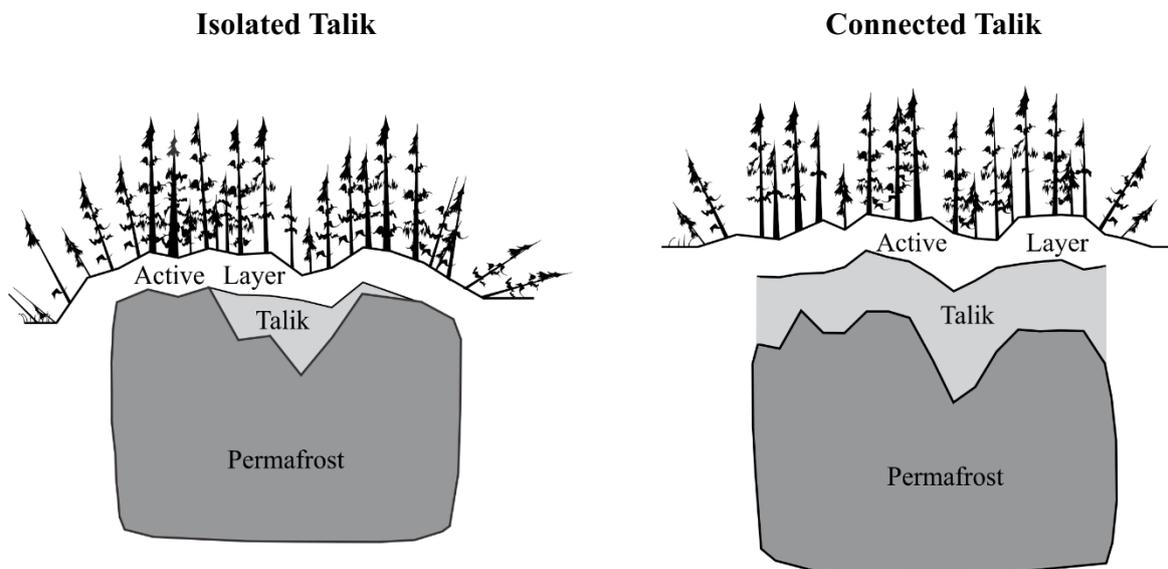
Figure 3: Taliks can either be isolated systems within a plateau, or continuous features across a plateau that connects adjoining wetlands. Adapted from Connon et al. (2018).
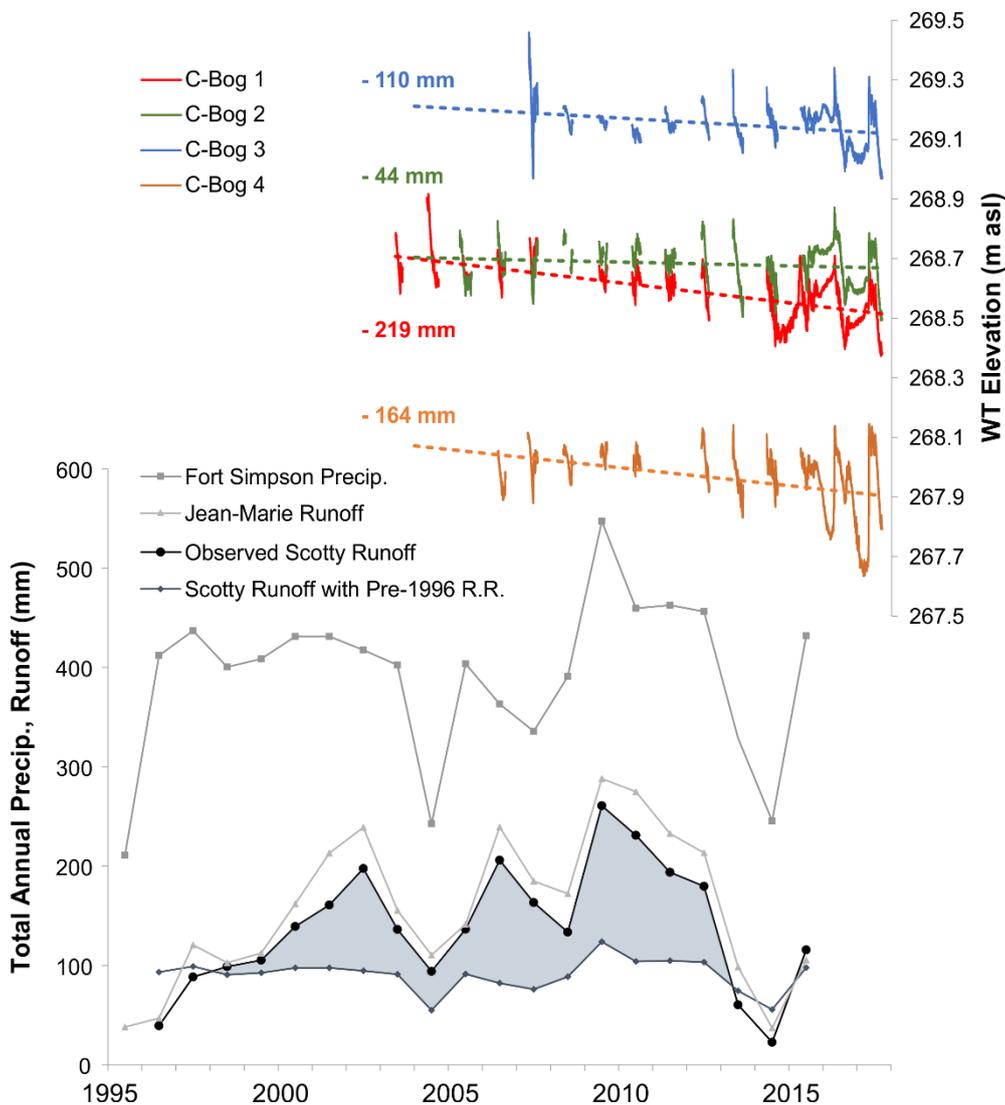
Figure 4: Wetland water loss at Scotty Creek for the overlapping period of the runoff and water level records. Adapted from Haynes et al. (In review).
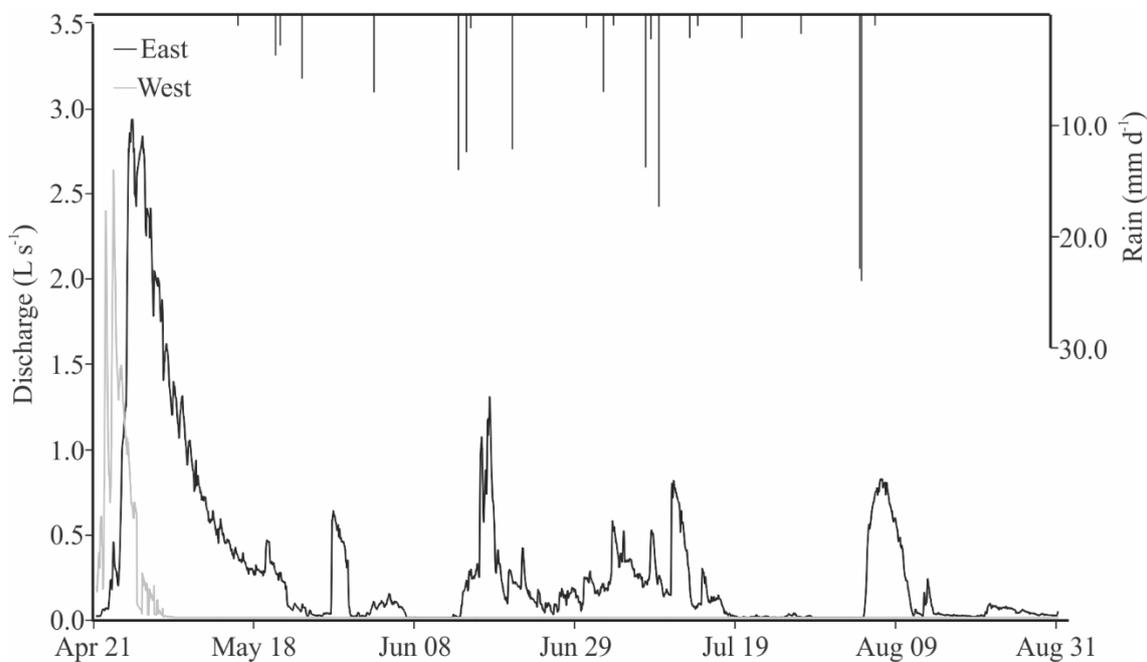
Figure 5: Hydrographs for two adjacent series of wetland cascades (East and West) during the summer of 2014. The plateau to wetland ratio of the East cascade is four times higher than that of the west cascade, explaining the differences in runoff magnitude between the two cascades. Adapted from Connon et al. (2015).
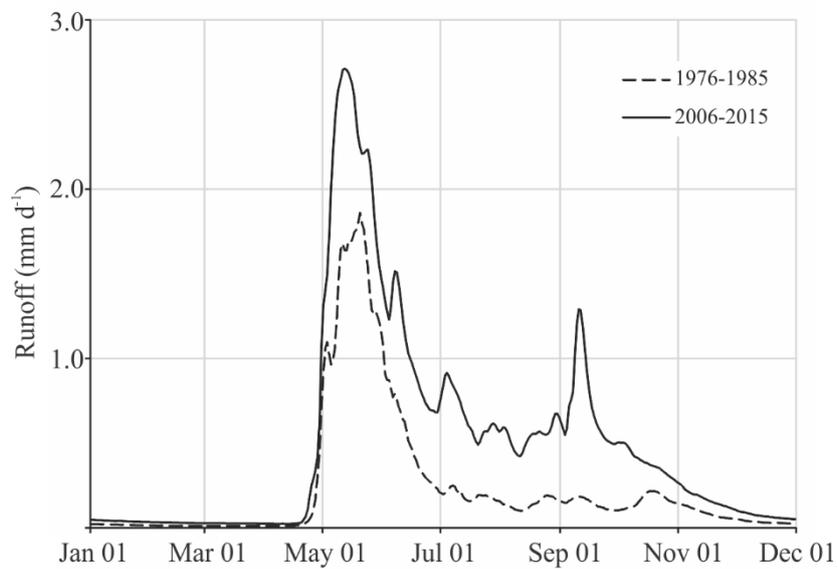
Figure 6: Composite hydrograph for two 10 year periods (1976-1985 and 2006-2015) of runoff from the Jean Marie River basin.