Hydrometeorological measurements in peatland-dominated, discontinuous permafrost at Scotty Creek, Northwest Territories, Canada

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Abstract
The discontinuous permafrost region of northwestern Canada is experiencing rapid warming resulting in dramatic land cover change from forested peatland permafrost terrain to treeless wetlands. Extensive research has been conducted throughout this region to gain insight into how climate-induced land cover change will impact water resources and ecosystem function. This paper presents a hydrological and micrometeorological dataset collected in the Scotty Creek basin, Northwest Territories, Canada over the period of 01 October 2014 to 30 September 2015, a sample of the intensive and coordinated measurements collected annually at this site. Micrometeorological data collected from four stations, one located in each of the land cover types representative of those comprising the Scotty Creek basin including bog, channel fen, stable peat plateau and peat plateau undergoing rapid permafrost degradation and loss, are presented. Monitored micrometeorological variables include incoming and outgoing shortwave and longwave radiation, air temperature, relative humidity, wind speed, precipitation (rain and snow) and snow depth. Deep ground temperatures (~1–10 m below the ground surface) from a channel fen as well as disturbed sites common to the basin including a seismic line and winter road are presented. Water levels were also monitored in the representative land cover types over this period. This dataset is available from the Wilfrid Laurier University Library Research Data Repository (https://doi.org/10.5683/SP/OQDRJG) and can be used in coordination with other hydrological and micrometeorological datasets to examine spatio-temporal effects of meteorological conditions on local hydrological responses across cold regions.

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1 | INTRODUCTION

The permafrost landscape across northwestern Canada is undergoing substantial land cover change as a result of rapid climate warming, particularly along the southern boundary of the discontinuous permafrost region (Jorgenson and Osterkamp, 2005; Quinton et al., 2011). Warming air temperatures threaten both the areal coverage and thickness of permafrost bodies via both lateral and vertical thaw in the discontinuous and sporadic permafrost zones (McClymont et al., 2013; Connon et al., 2018). The thickness of the layer of ground above permafrost (i.e. supra-permafrost layer) is expected to continue increasing as a result of warming (Lawrence et al., 2012; Frampton and Destouni, 2015), catalyzing the transition to thermokarst landscapes (Kokelj and Jorgenson, 2013). The supra-permafrost layer includes the active layer, which freezes and thaws annually, but may also include a perennially-unfrozen layer (i.e. talik) between the active layer and underlying permafrost (Mulier, 1947). A talik develops when the depth of thaw during summer exceeds the depth of re-freeze during winter, a process that can be initiated by an increase in air temperature, soil moisture, snow depth or other change increasing the heat flux into the ground (Åkerman and Johansson, 2008; Atchley et al., 2016). A talik accelerates permafrost thaw since it bounds the upper surface of permafrost (i.e. permafrost table) with a layer that is at or above the freezing point, and therefore eliminates the loss of energy from the permafrost during winter. As such, the formation of taliks may be instrumental in influencing the rate of permafrost thaw and altering the thermal and moisture regimes across the evolving discontinuous permafrost landscape (Connon et al., 2018).

The considerable observed land cover changes resulting in the loss of permafrost-cored peat plateaus (e.g. Beilman and Robinson, 2003; Pohl et al., 2009) significantly impact the cycling of water through these landscapes (Connon et al., 2014; Haynes et al., 2018b). Long-term increases in streamflow have been documented throughout the Northwest Territories (NWT), with the greatest increases in flow observed in the south-central NWT (St. Jacques and Sauchyn, 2009). In peatland terrain, the relative contributions of runoff sources have changed as the area contributing to basin runoff expands and previously isolated wetlands coalesce with the loss of permafrost (Connon et al., 2014). As permafrost degrades, raised plateaus subside resulting in the hydrological connection of previously isolated wetlands, including such common thermokarst features as collapse scar bogs surrounded by raised permafrost that typically store water, to the drainage network comprised primarily of channel fens. This process significantly alters the hydrological function of the different land cover types and the partitioning of water throughout the landscape (Quinton et al., 2011). Bogs in this region are defined predominantly as water storage features, particularly those isolated from the drainage network, receiving water from precipitation and as primary runoff from surrounding permafrost barriers (Connon et al., 2014). Channel fens are defined as water conveyances, directing to the basin outlet water received from precipitation, primary runoff from peat plateaus and secondary runoff from bogs that have developed a connection to the drainage network with the loss of permafrost barriers (Connon et al., 2014). Incremental additions of formerly isolated collapse scar bogs to the drainage network through the process of ‘bog capture’ (Connon et al., 2014) result in transient contributions to basin runoff as the storage function of these wetlands is lost (Haynes et al., 2018b). Permanent contributions to runoff from transitioning discontinuous permafrost basins result from the expansion of the drainage area, and account for the greatest contribution to the observed increases in runoff (Connon et al., 2014; Haynes et al., 2018b).

Field studies focusing on hydrology, meteorology and related fields have been conducted at Scotty Creek, NWT since the mid-1990s, with year-round monitoring since 1999. The aim of this long-term and ongoing research is to explore the dominant hydrological processes occurring in the discontinuous permafrost peatland landscape and examine the impacts of permafrost thaw-induced land cover change on these hydrological mechanisms. The direct effects of warming on the rate and pattern of permafrost thaw, the impacts of extreme events such as forest fires and anthropogenic influences such as the introduction of seismic lines on permafrost distribution are monitored in the Scotty Creek basin. In this paper, we present a hydrological and micrometeorological (including subsurface temperature and soil moisture) dataset from the Scotty Creek basin for the period of 01 October 2014 to 30 September 2015 (i.e. 2015 water year) (Haynes et al., 2018a). Data presented were collected from the land cover types representative of the Scotty Creek headwaters including peat plateaus (both thawing and stable), bogs and channel fens and includes data from instrumentation monitoring linear disturbances (seismic lines and former winter roads). This year of hydrometeorological data is an example of the intensive and coordinated measurements collected annually across the rapidly transitioning landscape of this long-term monitoring site.
2 | SITE DESCRIPTION

The Scotty Creek Research Station is located within the sporadic discontinuous permafrost zone in the NWT, Canada (61.44°N, 121.25°W), approximately 50 km south of Fort Simpson (Figure 1a,b). The mean annual air temperature (1981–2010) in Fort Simpson is −2.8°C with mean annual precipitation of 390 mm, of which approximately 38% (149 mm) falls as snow (Meteorological Service of Canada, 2017). Temperatures in this region have been steadily increasing, particularly during the winter months (Vincent et al., 2015), while annual precipitation has remained steady.

The Scotty Creek watershed covers 152-km² of subarctic boreal forest in the Taiga Plains ecozone. The watershed is comprised of heterogeneous upland moraines (48%), raised permafrost plateaus (20%), ombrotrophic bogs (19%), channel fens (12%) and lakes (2%) (Chasmer et al., 2014). The forested peat plateaus underlain by permafrost are dominated by an overstory of black spruce (Picea mariana), with an understory of Labrador tea (Rhododendron groenlandicum) and other ericaceous shrubs, lichens (Cladonia spp.) and mosses (Sphagnum spp.). Channel fens are dominated by floating vegetative mats comprised of predominantly Carex and Eriophorum sedges with individual tamarack (Larix laricina) and birch (Betula glandulosa) trees scattered throughout the fens (Garon-Labrecque et al., 2015). Bogs in this basin are vegetated with ericaceous shrubs including leatherleaf (Chamaedaphne calyculata), bog rosemary (Andromeda polifolia) and small cranberry (Vaccinium oxycoccos) (Garon-Labrecque et al., 2015). The dominant bryophyte species in the bogs include Sphagnum balticum and S. magellanicum (Garon-Labrecque et al., 2015) as well as S. riparium particularly in the wettest sites. Peat deposits in the basin range from a depth of 2–8 m (McClymont et al., 2013).

Permafrost at the study site is present only beneath raised forested peat plateaus and is maintained as a result of insulation by overlying peat and a relatively dry vadose zone. These peat plateaus act as runoff generators as their capacity for water storage...
Runoff from plateaus is directed to adjacent wetlands as supra-permafrost subsurface flow where it may be stored or further conveyed to the drainage network. As permafrost beneath peat plateaus degrades, the ground surface subsides and becomes inundated, resulting in the transition of raised plateaus to treeless waterlogged bogs and fens. Bogs isolated from the drainage network (i.e. channel fen networks) store water on the landscape and receive water from precipitation and as primary runoff from the surrounding elevated peat plateaus. In contrast, bogs connected to the drainage network due to a breach in the surrounding permafrost contribute water to basin runoff (Connon et al., 2014). Wide and hydraulically rough channel fens convey water through the watershed to the basin outlet (Hayashi et al., 2004). These land form types comprise the mosaicked, transitioning landscape of the discontinuous permafrost region.

3 | MICROMETEOROLOGICAL STATION DATA

Micrometeorological datasets are presented from four tripod stations located in land cover types representative of the Scotty Creek basin – bog, fen, stable peat plateau and thawing peat plateau (Figure 1c). The thawing peat plateau is undergoing rapid permafrost thaw and is actively transitioning to wetland. This dataset provides a contrast to the relatively unchanged plateau on which the stable plateau tripod is located. All data were reviewed for quality control and any calculations or corrections applied to the data are described below. The data were checked for gaps and reviewed to ensure that all measurement quality flags were within acceptable ranges. The data were also compared to data from other monitoring years to compare trends and seasonal means.

All data were recorded using Campbell Scientific dataloggers (CR10X or CR1000) with a measurement interval of 60 s and averaged data output every 30 min. A continuous record over the year is presented for each station, with the exception of the fen tripod, which has gaps in the data due to power and programming issues at the fen tripod, there are gaps in the data.
| Station       | Sensor                          | Parameter                  | Sensor height or depth (m) | Operating range          | Accuracy                                    |
|--------------|---------------------------------|----------------------------|---------------------------|--------------------------|---------------------------------------------|
| Bog          | Four Component Radiometer       | Net radiation              | 1.45                      | 0.3–50 μm                | ±10%                                        |
|              | (CNR1)                          | Temperature and Relative   | 1.9                       | Temp: −40 to +60°C       | Temp: ±0.2°C @ 20°C                        |
|              | Humidity Probe (HMP45C)         | Humidity                   |                           | RH: 0%−100%              | RH: ±2% @ 0 to 90% humidity                 |
|              |                                 |                            |                           |                          | ±3% @ 90 to 100% humidity                   |
|              | Met One Wind Speed Sensor       | Wind speed                 | 2                         | 0–60 m/s                 | ±0.11 m/s or 1.5% FS                       |
|              | Snow Depth Sensor (SR50A)       | Snow depth                 | 1.11                      | −45 to +50°C             | Maximum of ±1 cm or 0.4% of distance to target |
|              | Ground Heat Flux Plate (HFT3)   | Ground heat flux           | −0.05 m                   | −40 to +55°C             | better than ±5% of reading                  |
|              | Thermistors (107B)              | Ground temperature         | −35 to + 50°C             |                          | Worst case:                                 |
|              |                                 |                            |                           | −0.1 m                   | ±0.4°C (−24 to 48°C)                       |
|              |                                 |                            |                           | −0.2 m                   | ±0.9°C (−35 to 50°C)                       |
|              |                                 |                            |                           | −0.3 m                   | Interchangeability Error:                   |
|              |                                 |                            |                           | −0.4 m                   | ± 0.10°C (0-50°C)                          |
|              |                                 |                            |                           | −0.5 m                   | ± 0.20°C at −10°C                          |
|              |                                 |                            |                           | −0.6 m                   | ± 0.30°C at −20°C                          |
|              |                                 |                            |                           | −0.8 m                   | ± 0.40°C at −30°C                          |
|              |                                 |                            |                           | −1.0 m                   | ± 0.50°C at −40°C                          |
|              | Soil Moisture Sensor (Hydra     | Soil moisture              | −0.1 m                    |                          | Steinhart‐Hart                              |
|              | Probe II)                       |                            | −0.2 m                    |                          | Equation Error: ≤ ± 0.01°C (−35 to 50°C)    |
|              | Real dielectric permittivity    | Soil moisture              | 1 to 80 where 1 = air,   | ±≤1.5% or 0.2 whichever is typically greater |
|              | (isolated)                      |                            | 80 = distilled water      |                          | ±0.01 WFV for most soils ± ≤0.03 max for fine textured soils |
|              | Soil moisture for inorganic &   | Soil moisture              | From completely dry to    |                          | Steinhart‐Hart                              |
|              | mineral soil                    |                            | fully saturated           |                          | Equation Error: ≤ ± 0.01°C (−35 to 50°C)    |
|              | Bulk electrical conductivity    | Bulk electrical conductivity| 0.01 to 1.5 S/m          | Max. of ±2.0% or 0.02 S/m |
|              | Temperature                     | Temperature                | −10 to +55°C              | ± 0.3°C                   |
|              | Inter-sensor variability        | N/A                        |                           | ± 0.012 WFV (0 m²/m³)    |
| Fen          | Net Radiometer (NR-Lite)        | Net radiation              | 2.3                       | Spectral 0.2–100 μm      | Directional error: (0–60° at 1,000 W/m²): < 30 W/m² |
|              |                                 |                            |                           | (Measurement ± 2,000 W/m²) | Sensor asymmetry: ±5% typical, (±10% worst case) |
|              | Temperature and Relative        | Temperature and relative   | 2.33                      | Temp: −40 to +60°C       | Temp: ±0.2°C @ 20°C                        |
|              | Humidity Probe (HMP45C)         | Humidity                   |                           | RH: 0%−100%              | RH: ±2% @ 0%–90% humidity                  |
|              |                                 |                            |                           |                          | ±3% @ 90%–100% humidity                    |
|              | Met One Wind Speed Sensor       | Wind Speed                 | 2.53                      | 0-60 m/s                 | ±0.11 m/s or 1.5% FS                       |
|              | Snow Depth Sensor (SR50A)       | Snow depth                 | 1                         | −45 to +50°C             | Maximum of ±1 cm or 0.4% of distance to target |
| Stable plateau| Four Component Radiometer       | Net radiation              | 2                         | 0.3–50 μm                | ±10%                                        |
|              | (CNR1)                          | Temperature and Relative   | 2                         | Temp: −40 to +60°C       | Temp: ±0.2°C @ 20°C                        |
|              | Humidity Probe (HMP45C)         | Humidity                   |                           | RH: 0%–100%              | RH: ±2% @ 0%–90% humidity                  |
|              |                                 |                            |                           |                          | ±3% @ 90%–100% humidity                    |

(Continues)
radiation) was measured with a net radiometer (Kipp & Zonen, CNR1 in bog and plateaus; NR-Lite in fen). Annual Q* over the 2014–2015 water year was 1,574 MJ/m² in the bog, 893 MJ/m² on the stable plateau and 1,528 MJ/m² on the thawing plateau, where the variation is a result of differences in canopy coverage (Figure 2). Average annual water year Q* over the available micrometeorological station record up to 2016 for these sites were 1,512 MJ/m² in the bog (installed in 2004), 871 MJ/m² on the stable plateau (installed in 2007) and 1,409 MJ/m² on the thawing plateau (installed in 2004). The thawing plateau is rapidly losing tree canopy cover as the ground surface subsides and becomes inundated as a result of permafrost degradation. Air temperature and relative humidity were measured using a temperature and relative humidity probe (Campbell Scientific, HMP45C) mounted near the top of the six-foot tripods and housed in a passively ventilated Gill radiation shield (Figure 2). Mean annual air temperature measured at the bog, stable plateau and thawing plateau was −1.9, −2.0 and −1.4°C, respectively. Over the station record, mean annual air temperature was −2.4°C in the bog, −2.3°C on the stable plateau, and −2.0°C on the thawing plateau. Snow depth was also measured on the bog, fen and thawing plateau using an SR50A snow depth sensor (Campbell Scientific) and these data have been corrected for temperature. Wind speed in the bog and fen (Figure 2) was measured by a Met One Instruments wind speed sensor.
(Model #014A). The height, operating range and accuracy of all instruments located on the micrometeorological tripods can be found in Table 1.

Additionally in the bog and thawing plateau ground temperature and soil moisture were measured at several depths while ground heat flux was measured at a single depth. To monitor ground temperatures in the bog, thermistors (Campbell Scientific, 107B) were installed at 10, 20, 30, 40, 50, 60, 80 and 100 cm below the ground surface (Figure 3a). In an excavated and back-filled soil pit located centrally on the thawing plateau (see Hayashi et al., 2007 for details), ground temperatures were measured with thermistors installed at 0, 5, 10, 15, 20, 25, 30, 40, 50, 60 and 70 cm below the ground surface (Figure 3d). Soil moisture in the bog was measured at 10 and 20 cm below the ground surface (Stevens, Hydra Probe II Soil Moisture Sensor) (Figure 3b). The bog soil moisture and corresponding temperature record at 10 cm below the ground surface ends approximately 2 months prior to the end of the annual record due to a sensor error (Figure 3b). Using calibrated (Hayashi et al., 2007) water content reflectometers (WCR) (Campbell Scientific, CS615), volumetric water content at 10, 20, 30, 40 and 50 cm below the ground surface was monitored in the thawing plateau (Figure 3e). A sharp decrease in liquid volumetric soil moisture indicates soil freezing. Liquid water content of frozen soils at this site typically ranges from 0.15 to 0.2 (Connon et al., 2018). In

FIGURE 3 Mean daily ground temperatures measured at the bog (a) and thawing plateau (d), mean daily soil moisture (expressed as volumetric water content, VWC) for the bog (b) with corresponding ground temperature) and thawing plateau (e), and total daily ground heat flux (W/m²) for the bog (c) and thawing plateau (f)
both the bog and thawing plateau, ground heat flux (Qᵢ, W/m²) was measured using a ground heat flux plate (Campbell Scientific, HFT3) installed at 5 cm below the ground surface (Figure 3c,f), calibrated according to the method described by Hayashi et al. (2007) and calculated to include heat storage between the ground surface and ground heat flux plate.

4 | DEEP GROUND TEMPERATURES

To monitor ground temperatures at depth, deep thermistor (RBR, XR-420) strings were installed in water-jet drilled boreholes and recorded hourly temperature data at approximately 1 m depth intervals. Deep ground temperature datasets presented in this paper were located in a fen to a maximum depth of 6.4 m, a disturbed linear seismic line (cut in 1985) down to 9.28 m, and in two locations beneath an old winter road – one site with standing water (Winter Road Wet) to a maximum depth of 9.5 m and one without (Winter Road Dry) down to 8.92 m (see Figure 1c for measurement locations, Figure 4 for data).

5 | PRECIPITATION

5.1 | Total precipitation

Total precipitation, both rain and snow, was measured at half-hourly intervals using an Alter-shielded Geonor precipitation gauge (Model T200B; see Figure 1c for location of gauge). Data presented have been corrected for wind undercatch by determining precipitation type from hydrometeor temperature and adjusting for the catch efficiency of the gauge depending on wind speed measured at the height of the alter shield (Smith, 2007; Harder and Pomeroy, 2014). Total precipitation depth was recorded at 30-min intervals. Daily precipitation (rain, snow and total) is presented in Figure 5. In the 2014–2015 water year, 494 mm of total precipitation was received in the Scotty Creek basin, with approximately 45% of this (221 mm) occurring as snow. Average annual (water year) total precipitation over the record of the Geonor, which was installed in 2008 and includes up to 2015, was 482 mm. On average, 58% (281 mm) of this precipitation was in the form of rain, while 42% (201 mm) was received as snow.

5.2 | Snow surveys

Snowpack snow water equivalent (SWE) was determined prior to snowmelt in 2015 along established snow course transects, which traverse the representative land cover types including bogs, fens and peat plateaus (see Figure 1c for location of snow transects). In an effort to effectively capture the spatial variability of snow distribution, snow depth was measured using a steel ruler at intervals of 1–5 m. Snow water equivalent was determined at every fifth depth measurement point using a Prairie-type snow sampling tube (Geoscientific) (inner diameter: 6.18 cm) and hanging scale. Snow survey data presented here were collected on 23–24 March 2015, capturing snow depth and SWE just prior to the initiation of the snowmelt. Mean snow depth was 64.2 ± 10.8 SD cm on fen land cover
Snow density was similar across the land cover types with 0.204 ± 0.033 g/cm³ measured on fens (n = 5), 0.246 ± 0.036 g/cm³ on bogs (n = 31) and 0.232 ± 0.038 g/cm³ on peat plateaus (n = 19). Therefore, SWE ranged from 13.1 cm in the fen snowpack up to 18.0 cm on peat plateaus, with bog SWE measured to be 17.1 cm.

6 | WATER LEVEL

Water levels of individual wetlands and peat plateaus were monitored in single slotted stilling wells located at each site. Each well was equipped with either a Solinst (Levelogger Edge M2) or HOBO (U20-001-04) total pressure transducer. Data were recorded at 30-min intervals and were corrected for
barometric pressure (Solinst Barologger Gold) in buffered thermal conditions (McLaughlin and Cohen, 2011). Water level data presented in this paper are from land cover types representative of the basin including a channel fen (Fen), a thawing peat plateau (Thawing Plateau), a bog isolated from the drainage network (Isolated Bog) and two bogs with differing degrees of drainage network connection (Fully Connected and Partially Connected Bog) (see Figure 2c). The pressure transducer in the channel fen was lowered in the well over the winter season to prevent sensor freezing and provide a continuous record for this water year (Figure 6). Pressure transducers were installed in the Partially Connected Bog and Thawing Plateau wells on 3 May 2015, while those in the Fully Connected and Isolated Bogs were installed on 21 May 2015, once the wells were ice-free (Figure 6). Water level records for the 2015 growing season are provided in this dataset. Pressure transducer data were related to the manual measurements from the top of the well casing (ToC) to the water table at sensor installation and confirmed with the same measurements at sensor removal. The water level record standardized with the installation manual measurements was within 0.9 ± 1.1 cm ($n = 5$ sites in 2015) of the manual measurements at sensor removal. The water level data are presented in units of metres above sea level (m a.s.l.) as well top of casing positions were surveyed in May 2015 using a differential global positioning system (SR530 RTK, Leica Geosystems Inc.).

7 | DATASET LOCATION AND FORMAT

All data presented in this paper are available from the Wilfrid Laurier University Library Research Data Repository (https://doi.org/10.5683/SP/OQDRJG). The dataset is under an embargo period, during which time access to the dataset may be requested by creating a Dataverse account (providing name, institution and e-mail address). The datasets are provided in four tab-delimited files. Each file may be downloaded individually as an Excel file. Each of the four dataset files contains a metadata worksheet defining the data columns, applicable units and other pertinent information.

8 | SUMMARY

The data presented in this paper comprise 1 year of the long-term hydrological, micrometeorological and geophysical research conducted in the Scotty Creek basin examining the effects of permafrost loss on ecosystem change. The landscape of the discontinuous permafrost zone is undergoing rapid transition due to warming-induced permafrost thaw, with peat plateaus subsiding and becoming inundated by adjacent wetland features including bogs and fens. Vertical energy exchange with the atmosphere is an important control on the degradation and thaw of permafrost in this region. This energy component, as well as advective energy transfer from flowing water in adjacent wetlands, is responsible for the rapid landscape change from permafrost plateaus to wetland areas. Therefore, comparing the energy balances of a thawing plateau and a relatively stable plateau, as well as wetlands including bogs and fens, provides important information regarding the driving influence of discontinuous permafrost thaw. Human disturbance is also catalyzing significant landscape change in this region, including the establishment of winter roads and the cutting of seismic lines for oil and gas exploration. Combined, this hydrological and micrometeorological dataset would be useful in making comparisons to other regions to investigate the spatio-temporal variability in hydrological responses to micrometeorological factors and
in validating efforts to model the hydrological and energy dynamics of this changing landscape.

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OPEN PRACTICES

This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available at https://doi.org/10.5683/SP/OQDRJG Learn more about the Open Practices badges from the Center for Open Science: https://osf.io/tvyxz/wiki.

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