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SCIENTIFIC BRIEFING

Subsurface flow measurements using passive flux meters in variably-saturated cold-regions landscapes

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Abstract

To date, passive flux meters have predominantly been applied in temperate environments for tracking the movement of contaminants in groundwater. This study applies these instruments to reduce uncertainty in (typically instantaneous) flux measurements made in a low-gradient, wetland dominated, discontinuous permafrost environment. This method supports improved estimation of unsaturated and over-winter subsurface flows which are very difficult to quantify using hydraulic gradient-based approaches. Improved subsurface flow estimates can play a key role in understanding the water budget of this landscape.

KEYWORDS

Darcy flux, frozen subsurface flow, hydraulic gradient, passive flux meter, time-integrated measurements, uncertainty, unsaturated flow

1 | INTRODUCTION

Field test measurements of saturated lateral subsurface fluxes are typically determined through the application of Darcy's law, which depends on the spatially and temporally variable hydraulic gradient and hydraulic conductivity. Measurement of fluxes in variably saturated porous media using the Darcy-Buckingham equation is even more uncertain, as local gradients may dominate and conductivity varies dramatically with saturation (Winter, 1983). Though methods exist to determine the unsaturated hydraulic conductivity (e.g., Ankeny, Ahmed, Kaspar, and Horton (1991)), the cross-sectional area of the saturated and unsaturated profile are hard to predict, and water retention curves are known to demonstrate hysteretic behaviour (Naasz, Michel, & Charpentier, 2005). Lastly, over-winter flux predictions are unreliable in cold regions. This is due to the sensitivity of hydraulic conductivity to partial and complete freezing in soils (Lebeau & Konrad, 2012), and the effect of near-freezing temperatures, the formation of ice cover and subsequent snow accumulation in wetland features on measured hydraulic gradients.

Annable et al. (2005) proposed a novel method for measuring temporally averaged sub-surface flow using Passive Flux Meters (PFMs). This method deploys a tracer-impregnated, activated charcoal filled cartridge into a well or piezometer. Subsurface flow through the meter causes the de-soprtion of multiple tracers at (different) known rates, allowing the user to determine the flux of water through the cartridge over the period of observation (Hatfield, Annable, Cho, Rao, & Klammler, 2004; Hatfield, Rao, Annable, & Campbell, 2002). These PFMs have predominantly been used in contaminant monitoring in which contaminants are sorbed while the known tracers are desorbed (Desormeaux, Annable, Dobberfuhl, & Jawitz, 2019; Haluska, Thiemann, Evans, Cho, & Annable, 2018; Hatfield et al., 2004; Klammler, Hatfield, & Annable, 2007; Kunz et al., 2017; Lee et al., 2007) but they also provide reliable time-integrated subsurface flux measurements.

PFMs have mainly been used in relatively high flux groundwater studies, and have not yet been deployed under freezing conditions or in low hydraulic gradient sites. Though they have been used in a glaciated watershed to determine fluxes in various soil zones (Benton et al., 2018), the study was of short duration, and did not include the freezing season. The use of PFMs in low hydraulic gradient wetlands interspersed with permafrost and subject to seasonal freeze–thaw is considered here as a means of estimating otherwise highly uncertain water fluxes through variably saturated, variably frozen soils. Results from the PFMs (with uncertainty bounds) are compared to gradient-based measurements for

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the thawed season, and unsaturated and over-winter data are presented for this novel method.

2 | METHODS

This study was undertaken at the Scotty Creek Research Station (SCRS) located approximately 70 km south of Fort Simpson in the Northwest Territories, Canada (Quinton et al., 2019). This region is dominated by discontinuous permafrost peatlands, in which permafrost-free wetland features can be (ephemerally) connected through perennially thawed soil layers (taliks) located within permafrost-cored peat plateaus. Subsurface flow through taliks (as shown in Figure 1b is determined by the seasonally variable hydraulic gradient between the wetlands, as well as the hydraulic conductivity. Understanding the magnitude and direction of subsurface flow is critical in defining the water and energy balance in this flat landscape. Three sites with taliks were selected, two between a collapse-scar bog and a fen, and one between two collapse-scar bogs, where subsurface flow was suspected based on permafrost thaw rates and measured hydraulic gradients. Specific sites were selected based on aerial imagery indicating adjacent wetland features, and verification of talik presence using a frost probe (graduated steel rod).

Five 1.2 m long PFMs obtained from EnviroFlux (further details in Hatfield et al. (2002)) were installed in the three sites described above, where two instruments were installed at each site with the exception of one bog-fen connection. The exact location of installation was chosen where the permafrost table was approximately 1.2 m below the ground surface, such that the PFM recorded flow through the entire supra-permafrost layer (locations shown in Figure 1a). For smooth installation, a 5 cm pilot hole was augured to the permafrost table before the PFM was installed in a PVC well slotted from it's base to approximately 15 cm below the ground surface, as shown in Figure 1b. The length of the PFM is composed of a pre-loaded tracer sorbent matrix in a permeable casing and covered in a plastic protective sheathing. This unit is mounted around a section of 1/4″ PVC tubing. The PFM is shipped and stored in a sealed PVC casing, and is transferred directly from this casing to the well to avoid contamination and deformation (Annable et al., 2005). Due to the relatively high hydraulic conductivity of near-surface peat, it was known that the PFM would not act as a preferential flow path, and should therefore not disturb the subsurface fluxes as the hydraulic conductivities of peat and the activated carbon are similar (Annable et al., 2005; Dalahmeh et al., 2012; Quinton, Hayashi, & Carey, 2008). The top of the casings were sealed against vertical water inputs from precipitation. All PFMs were installed within 2 days of August 23, 2018.

The PFMs remained installed over winter. Two were removed within 2 days of April 10, 2019, (picture just prior to removal in Figure 1a) while the remaining instruments were retrieved at the end of the thawing season, within 2 days of September 19, 2018. In order to remove the PFMs in the spring (while the ground was still frozen) small resistance heater strips were affixed to an aluminium rod that was inserted into the central tube of the PFM and left for 24–48 hours attached to a deep-cycle marine battery and a solar array. This sufficiently thawed the PFM to allow it to slide out of the well. Once removed, the PFMs were sub-sectioned into two 60 cm segments in the spring, or five 24 cm segments in the fall. Sections were evenly spaced along the PFMs. Sorbent at each sampling depth was well mixed, sub-sampled, and carefully packaged for analysis, using the methodology set forth by Hatfield et al., 2004. Once the samples were collected, they were shipped to the PFM manufacturer EnviroFlux for tracer analysis to determine the total flux through the meter over the period of installation.

Flux measurements were compared to groundwater flow – an application of Darcy's law ($q = K \nabla h$, where q is the flux, K is the saturated hydraulic conductivity and h is the hydraulic head). The

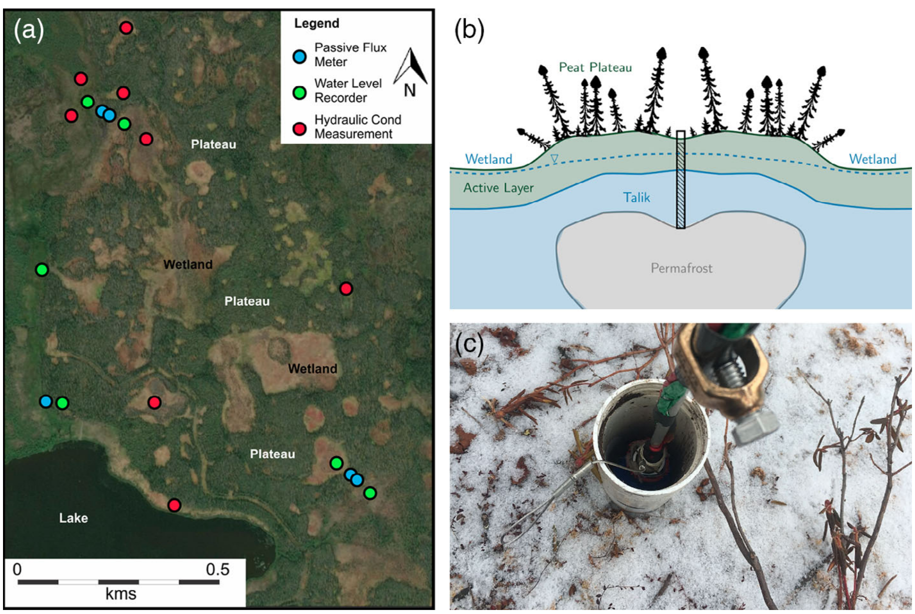

FIGURE 1 Site map of instrument locations in (a), (b) Schematic diagram of PFM installed on a plateau containing a talik that connects two wetland features. Blue regions are perennially thawed and thus allow for year-round flow. Hatched region indicates slotted depth of PFM well. Trees are not to scale.
(c) photograph of PRM removal in early spring (April 10)

hydraulic gradient for this approximation was determined using HOBO U20L pressure transducers (termed water level recorders – WLRs), surveyed to a common datum, that were used to determine water level. Pairs of WLRs were installed at each study site up-gradient and down-gradient from each PFM. Only two WLRs were required as flow perpendicular to the narrow channel connecting the adjacent wetland features was assumed to be negligible (Figure 1b). Water level was measured at half-hour intervals for the entire study period. Saturated hydraulic conductivity was determined at variable depths and in different locations in the SCRS using rising and falling head tests (summarized in Table S1 of the Supporting Information). For these tests, a pressure transducer recording at 1 s intervals allowed for high resolution water level tracking in the drive-point piezometer. Tests were performed both during the thawing season and once all ground ice was thawed. These data were augmented with select data from Quinton et al. (2008) using Guelph permeameter tests in the high-conductivity near-surface peat, including the data collected between 20 and 40 cm depth.

3 | RESULTS AND DISCUSSION

Figure 2 compares the average summer flux measured using PFMs and the gradient-based approach at all three study sites. The estimated uncertainty in the passive flux meter readings is of up to ±25% primarily due to uncertainty in sorption/de-sorption rates, but including spatial variability of hydraulic properties and flow paths and well geometry, though it may be as low as 5%, depending on the degree of de-sorption (Hatfield et al., 2004). This uncertainty is shown as coloured shaded region in Figures 2 and 3, and is small compared to the combined uncertainty in the measured spatially integrated hydraulic gradient and saturated hydraulic conductivity. The uncertainty in gradient combines the sensitivity of the WLRs, and the Differential Global Positioning System (DGPS) elevation data and separation resulting in up to 2% error. Point measurements of hydraulic conductivity were spread across the SCRS in order to quantify the spatial variability which was found to be comparable to the variability in data collected in the same location. In order to capture the spread of values observed at the SCRS, all of the data collected using rising and falling head tests, as well as laboratory analyses, were combined by depth, and for each depth the range between the maximum and minimum hydraulic conductivity reported at that depth was used as a measure of uncertainty. A combination of the uncertainty in hydraulic gradient and saturated hydraulic conductivity results in the grey shaded region in Figure 2, though the variation in saturated hydraulic conductivity clearly dominates the uncertainty.

Significantly more sources of measurement error are present in the gradient-based estimation. Firstly, the measurement of the gradient is subject to measurement errors stemming from pressure transducer accuracy and barometric pressure correction as well as DGPS accuracy in both elevation and Euclidean distance between sensors. Additionally, the over-winter gradient provided from the sensors is unreliable due to near-freezing temperature induced changes in pressure, ice cover and snow load. The hydraulic conductivity is also subject to measurement error. It is made as a point measurement in both space and time, and it is vertically integrated over the screened depth of the piezometer, potentially averaging vertically differing layers. Not only are slug tests and pump tests susceptible to multiple sources of

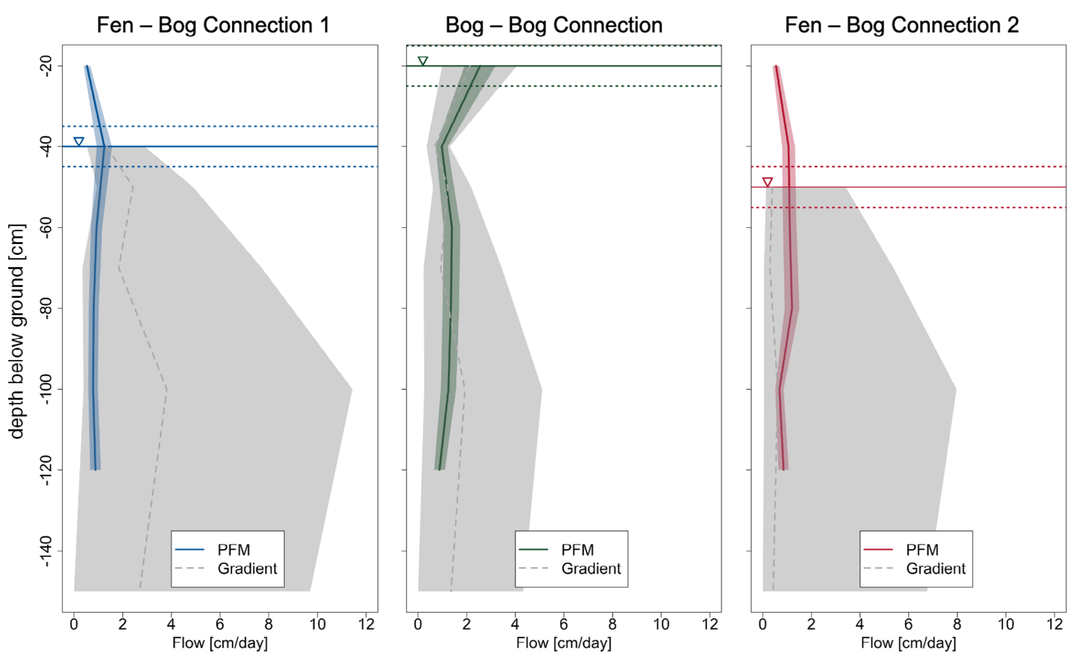

FIGURE 2 Comparison of summer flow at three sites using PFMs (coloured lines) and the Darcy groundwater flow technique (dashed grey lines and shaded region). Average water table at each site indicated with a horizontal line, while dashed lines indicate the seasonal variation in water table

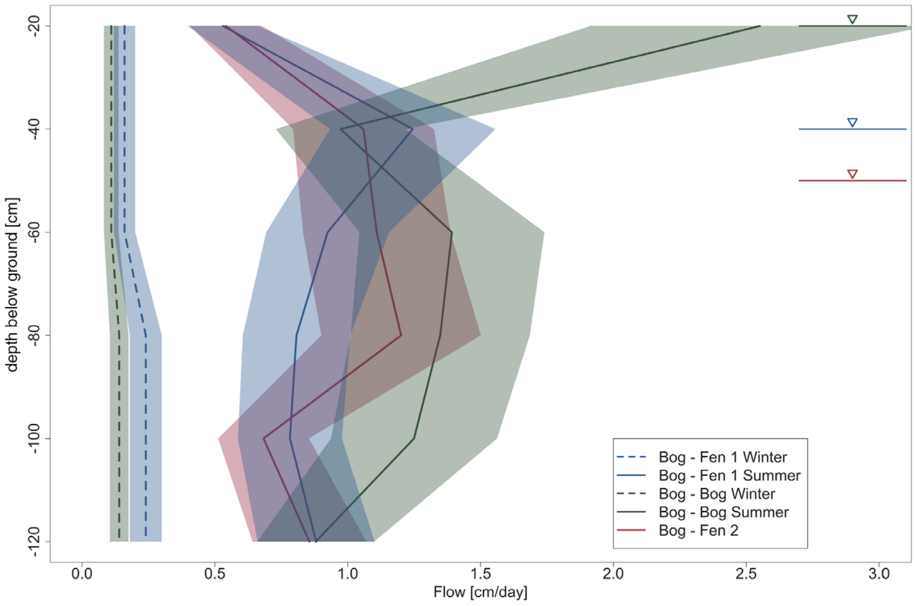

FIGURE 3 Comparison of mean PFM-estimated summer flux at all sites and winter flux for two of the three instrumented sites. Note the linear scale on the x-axis, where hydraulic conductivity is usually reported on a log scale

measurement error due to well screen placement and geometry, boundary effects and well-skin effects (disruptions to the flow field due to the presence of a well, or disturbance of soil around well during installation) (Hyder, Butler Jr, McElwee, & Liu, 1994), but hydraulic conductivity is known to be highly spatially variable (within 2–3 orders of magnitude) (Gupta, Rudra, & Parkin, 2006; Sudicky, 1986), and repeated measurements made under identical conditions can report highly varying values (Chappell & Lancaster, 2007). The Darcy flux approach is only applicable to a strictly saturated and thawed soil, and therefore is subject to significant error in unsaturated or partially frozen systems. Finally, as freezing occurs, the flow face available for flux shrinks at some unknown rate due to reduced (and unknown) hydraulic conductivity in frozen soils (Kurylyk & Watanabe, 2013). Gradient-based flow estimation is therefore not only subject to higher uncertainty, but it is unable to provide flux estimates in unsaturated and/or frozen conditions.

The seasonal PFM data is shown in Figure 3, indicating that 28% of annual flow occurs over-winter at Bog-Fen Connection 1, and 13% at the Bog-Bog Connection. The winter flux and summer flux in the saturated region are similar between sites, indicating relatively low spatial variability in time-integrated flux. Below the water table, these measurement ranges are overlapping indicating that the spatial variability of flow at each site is likely captured within the error bounds placed on the measurement. The over-winter data are not compared to the gradient-based method because the over-winter gradient is unreliable due to pressure artefacts caused by near-freezing temperatures (induced by the Clausius-Clapeyron relation, [Kurylyk & Watanabe, 2013]) and snow loading, and there was no hydraulic conductivity data available for either unsaturated, partially frozen or completely frozen profiles.

Figure 3 shows that the PFMs have the potential to address both of the shortcomings of the gradient-based approach, as they provide a direct and temporally integrated measurement of the flux, independent of hydraulic gradient and conductivity. The summer data from the bog – bog connection aligns very well with the gradient-based calculation in Figure 2. This location maintains a water table near the soil surface, however, the other two sites have an average water table position at a depth of 40 cm or more (Figure 2). In these sites, the near-surface flux reported by the PFMs is significantly lower, but cannot be compared to an estimate using the gradient-based approach. The measured flux through the PFM may be affected by the capillary barrier effect, as described by Stormont and Anderson (1999), where preferential flow may occur within the activated carbon of the PFM due to its low porosity relative to the adjacent peat. That being the case, Price and Ketcheson (2009) discuss the importance of moisture wicking in unsaturated peat as a mechanism for vertical water transfer, and Quinton, Elliot, Price, Rezanezhad, and Heck (2009) discuss the structure of peat which lends itself well to unsaturated vertical water transfer, and may therefore limit the effect of boundary flow. More work needs to be done using PFMs in unsaturated environments to better characterize unsaturated fluxes.

Instruments do exist that allow for the measurement of soil tension and unsaturated hydraulic conductivity, though estimates of unsaturated hydraulic gradient are extremely uncertain due to soil heterogeneity (strongly affected by pore size distribution which is not spatially homogeneous) (Hallett, Nunan, Douglas, & Young, 2004; Hayashi, van der Kamp, & Rudolph, 1997; Richards, 1942). Tensiometers capable of reporting unsaturated soil tension are however confounded by the freeze/thaw process due to it's impact on pressure gradients (Kurylyk & Watanabe, 2013), as well as potential freezing damage to the instruments (Fredlund, Gan, & Rahardjo, 1991). Due to fluctuations in water table position, variability in unsaturated hydraulic conductivity depending on soil material, and hysteretic behaviour based on antecedent conditions, the PFMs are a valuable alternate method to accurately report subsurface flux both on the short-term, as suggested by Annable et al. (2005), but also on the scale of months in low gradient landscapes as presented here.

Over-winter mean fluxes measured using the PFMs are reported as dashed lines in Figure 3. This flux cannot be calculated using gradient-based methods, but aligns well with theory. The maximum extent of the freezing front extends to 52 cm below the ground surface at Bog-Fen Connection 1 and 56 cm below the surface at Bog-Bog Connection. This is reflected in the near-zero flux reported at the surface. Bog-Fen Connection 1 thawed earlier than the Bog-Bog Connection due to the presence of warmer fen water, resulting in the higher winter flows reported in this site. Higher flow rates at depth confirm suspected over-winter talik flow, as near-surface flows are higher during the thawed season. Additional evidence for talik flow exists in the form of over-winter permafrost degradation observed at Bog-Fen Connection 1, where 21 cm of thaw was observed between August 2016 and May of 2017 and 13 cm of thaw between September 2017 and April of 2018. The ability to quantify over-winter flux through talik connections allows to better quantify the role of advection in driving permafrost degradation, as outlined in Devoie, Craig, Connon, and Quinton (2019); Kurylyk, Hayashi, Quinton, McKenzie, and Voss (2016); McClymont, Hayashi, Bentley, and Christensen (2013).

Prior applications of PFMs show that the main shortcoming of these instruments is that long-term measurements are subject to increased error as the tracer concentrations may be depleted below the linear tracer elution limit (Hatfield et al., 2004). The presence of flow reversals, while a concern for contaminant monitoring (Hatfield et al., 2004), is not a concern for flux measurement as the water passing through the PFM carries only a small concentration of sorbent, and therefore can remove additional tracer from the PFM when flowing in the opposite direction. This is advantageous as studies considering advection are generally more concerned with the total flow than the net flow, and the calculated Darcy groundwater flow also reports total flow.

4 | CONCLUSION

PFMs provide measurements of subsurface fluxes consistent with current field measurement techniques, while reducing measurement uncertainty. This technology can estimate flux rates in variably saturated and variably frozen soil columns, whereas the gradient-based technique is likely to fail under these conditions. Though results are presented for discontinuous permafrost peatlands, they may be transferable to other wetland landscapes in which high measurement accuracy is desired, soils are variably saturated and/or variably frozen. This work is the first known application of PFMs for evaluating subsurface hydrologic fluxes in permafrost terrains.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the Wilfrid Laurier University Library archive https://dataverse.scholarsportal.info/dataset.xhtml?persistentId=doi:10.5683/SP2/YR6TQ8

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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