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Discussion

Disconnected active layers and unfrozen permafrost: A discussion of permafrost-related terms and definitions

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HIGHLIGHTS

- Permafrost remains at or below 0°C for at least two years regardless of the pore water phase, but the active layer must undergo phase change
- Frozen ground can dominate the form and function of landscapes because pore ice is structurally solid and relatively impermeable
- Temperature alone is insufficient to describe soil thermal state as freeze/thaw accounts for more than 80% of the energy transfer typically
- Permafrost microbial communities are driven by soil unfrozen water content as well as temperature

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ABSTRACT

Permafrost is ground that remains at or below 0 °C for two or more consecutive years. It is overlain by an active layer which thaws and freezes annually. The difference between these definitions – the active layer based on pore water phase and permafrost based on soil temperature – leads to challenges when monitoring and modelling permafrost environments. Contrary to its definition, the key properties of permafrost including hardness, bearing capacity, permeability, unfrozen water content, and energy content, depend primarily on the ice content of permafrost and not its temperature. Temperature-based measurements in permafrost systems often overlook key features, e.g. taliks and cryopegs, and comparisons between measured and modelled systems can differ energetically by up to 90 % while reporting the same temperature. Due to the shortcomings of the temperature-based definition, it is recommended that an estimate of ice content be reported alongside temperature in permafrost systems for both in-situ measurements and modelling applications.

Plain language summary: Permafrost is ground that remains at or below 0 °C for two or more consecutive years. Above it sits an active layer which thaws and freezes annually (meaning that the water in the ground changes to ice each winter). The difference between these definitions – the active layer based on the state or water in the ground and permafrost based on ground temperature – leads to challenges when measuring (in the field) and modelling (using computers) permafrost environments. In addition to these challenges, the key properties of permafrost including its ability to support infrastructure, convey water, and absorb energy depend more on its ice content than its temperature. Due to the shortcomings of the temperature-based definition, it is recommended that an estimate of ice content be reported alongside temperature in permafrost systems for both field measurements and modelling applications.

1. Introduction

The active layer is 'the top layer of ground subject to annual thawing and freezing in areas underlain by permafrost', a definition based on the phase of the pore water contained in the ground (Associate Committee on Geotechnical Research, hereinafter (ACGR), 1988). In contrast,

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permafrost is defined on the basis of temperature, as 'ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two years' (ACGR, 1988; Van Everdingen, 1998). Though these definitions may seem consistent – pure water does freeze at 0 °C – pore water pressure (Zhang et al., 2022) and sorptive forces between soil particles and water molecules (Ma et al., 2017) both result in pore water phase change occurring over a range of sub-zero temperatures (Teng et al., 2021). As a result, ground at sub-zero temperatures contains a significant quantity of unfrozen water (Buehrer and Rose, 1943, Nersesova and Tsytovich, 1963, Koopmans and Miller, 1966, and many others).

The relationship between the unfrozen water content of a soil and its temperature is governed by a soil freezing characteristic curve (SFCC) (Koopmans and Miller, 1966). SFCCs are strongly affected by soil texture and solute presence, and exhibit hysteresis between the freezing and thawing limbs (Ren and Vanapalli, 2020, Zhou et al., 2020, Jing-yuan et al., 2020). Most often measured in the laboratory setting, SFCCs are challenging to quantify and are often approximated by simple mathematical relations fit to relatively sparse available data (Ren et al., 2018, Devoie et al., 2022a, 2022b – Fig. 1). As shown in Fig. 1, at temperatures significantly below zero, the unfrozen water content of the soil reaches a residual level, at which point the soil is considered 'completely frozen' (Anderson and Tice, 1972).

The diversity of SFCCs (Devoie et al., 2022a, 2022b) complicates the discussion of permafrost and active layer, and Fig. 2 (modified from ACGR) (a) shows a typical profile of a permafrost system. In this figure, the active layer encompasses the top layer of permafrost (that never exceeds 0 °C) but thaws according to an SFCC, here termed 'seasonally active permafrost'.

In warm discontinuous or relict permafrost systems, "permafrost exists in a slowly degrading state" and is not in equilibrium with the climate (Lunardini, 1996; Bonnaventure and Lamoureux, 2013; Walvoord and Kurylyk, 2016). In such systems, a talik often exists between the base of the active layer and the permafrost as shown in Fig. 2b (Connon et al., 2018). Taliks are defined as "perennially thawed regions of ground found in a permafrost environment and may be either between

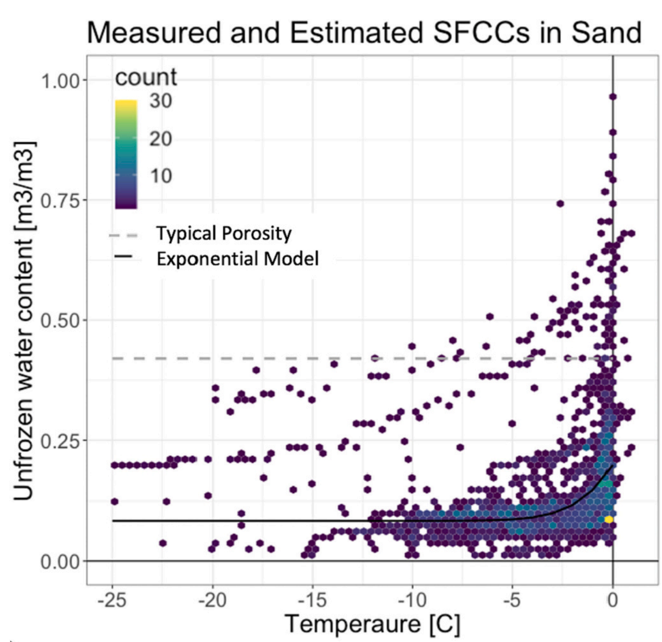

Fig. 1. SFCC data from literature describing variably saturated sandy soils (heatmap scatterplot) fit with typical SFCC model based on an exponential relation. Note that for these sandy soils liquid water is present, and the residual water content of the best-fit is approximately 10 %, with liquid water ranging from approximately 30–60 %. The typical porosity of sand is indicated by the grey dashed line to assist in data interpretation (Curry et al., 2004).

the base of the active layer and permafrost, or within a permafrost profile", shown in Fig. 2b (Muller, 1947). Muller (1947), and later Connon et al. (2018), suggested that the term *suprapermafrost layer* be used to "describe the combined thickness of the active layer and talik". In more recent publications, the term "depth to permafrost" has been used to account for this combined thickness (e.g. Rey et al., 2020; Disher et al., 2021). Field investigations frequently measure the end-of-season thaw depth (e.g. Hinkel and Nelson, 2003), and report this depth as the active layer, though it is more aptly described as the depth to permafrost without verification of refreeze depth.

In a warming cryosphere, permafrost systems (i.e. profiles including active layer, permafrost, and, if present, taliks) affect about 22 % of the exposed land in the Northern Hemisphere, and are warming to temperatures at which the ground has significant liquid water content according to their SFCCs (Nicolsky and Romanovsky, 2018; Obu, 2021; Devoie et al., 2022a, 2022b; Chuvilin et al., 2022). It is in such cases that the temperature-based definition of permafrost and the phase-based definition of the active layer, often leads to confusion and therefore misrepresentation. Specifically, such confusion can compromise the accuracy of numerical descriptions of the processes and properties that govern the structural, hydrologic, microbial, and thermodynamic functioning of warming permafrost systems (Tarnocai et al., 2004; Brown et al., 2008; Bonnaventure and Lamoureux, 2013; Walvoord and Kurylyk, 2016). Five specific aspects of these definitions are often misinterpreted in the current literature, and each of these is described below with recommendations on how to avoid common misconceptions.

2. Where definitions fall short

2.1. Soil structure: infrastructure damage, frost action, slope failure, and their prediction

When considering systems through a geotechnical lens, both the active layer and permafrost are of interest because they are *solid*, and not because they are cold. The thermal definition is therefore incomplete without an accompanying SFCC, as the structural properties of the material are dependent on pore ice content (Williams, 1995; Wang et al., 2022). This is a growing concern in regions with infrastructure on a foundation of warming permafrost (Aldaeef and Rayhani, 2018). Similarly, an assessment of slope stability and the potential for thaw-induced slumps, slides, and other mass movements is closely linked to the ground ice content (inclusive of pore ice and ice lenses) through the soil mechanical properties (Yang et al., 2022). In these cases, direct measurement of ice content and/or ice content-dependent mechanical properties (e.g. shear strength) and not just the temperature should be considered best practice, as recommended by Arenson et al. (2004).

The structural properties of frozen soils are closely linked to the processes of frost heave and subsidence. Due to the difference in density between liquid water and ice, it is common for freezing and thawing soils to expand and contract as their pore water changes phase and as ice lenses develop and degrade (Woo, 2012, p. 59). This can be extremely damaging to linear infrastructure such as roads, rail lines and pipelines which are sensitive to small vertical displacement (Ma et al., 2016; Oswell, 2011). Not only is seasonal freeze/thaw cycling of concern, permafrost thaw-induced ground subsidence can have even more serious implications for infrastructure (Raynolds et al., 2014; Hjort et al., 2022), especially where subsidence rates vary over relatively short distances. Finally, the existence of segregated ground ice (pure ice lenses) in a permafrost profile can lead to catastrophic failure of the ground surface and is linked to sink holes, lake drainage, and areas of exaggerated freeze/thaw damage (i.e. retrogressive thaw slumps) (Fortier et al., 2007), especially where the ground surface is sloping. Though less common in a warming climate, the formation of these ice lenses can also cause significant disruptions including damage to infrastructure in permafrost systems (Konrad and Morgenstern, 1981).

Both the structural properties of soils and their volume change are

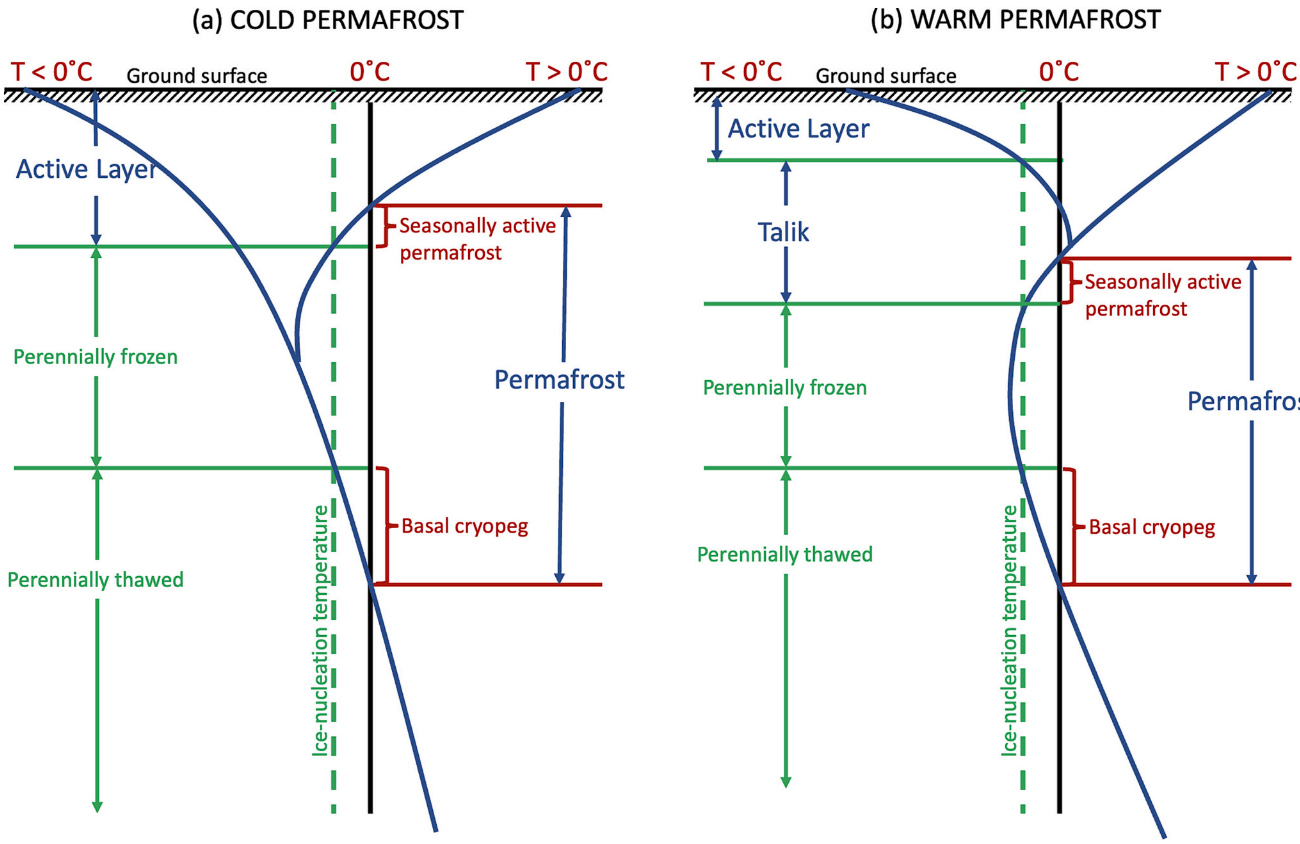

Fig. 2. Terms used to describe the ground temperature and state of water versus depth in a cold (a) and warm (b) permafrost environment. The ice-nucleation temperature is used to define the base of the active layer, and not the residual water content or any other ice fraction. Thicknesses of each layer are not to scale. The warm permafrost (b) panel may or may not include a talik.
Modified from ACGR, modified from Van Everdingen (1998).

directly linked to ice content rather than to ground temperature. Ice content and total soil water content therefore merits reporting in the context of infrastructure development and maintenance, where ground temperature alone is an inadequate measure of freeze/thaw state as the subsurface warms.

2.2. Soil energy content: latent and sensible heat, thermal buffers, and thaw rates

The thermal state of permafrost depends significantly more on its ice content than its temperature. Hayashi et al. (2007) measured that >86 % of the summer ground heat flux contributed to the melting of soil pore ice in a peatland system. In saturated mineral soils, latent heat can account for >90 % of the energy in the system. Latent heat plays a smaller role in dry or low-porosity systems, but should not be neglected in those subject to phase change. Nicolsky and Romanovsky (2018) have illustrated that fine-grained soils with significant unfrozen liquid water content at temperatures below 0 °C have significantly slower warming rates due to phase change.

In a warming climate a small change in the ground surface energy balance of the system has been shown to initiate the formation of a talik between the active layer and permafrost (Farquharson et al., 2022). By definition, the talik remains thawed, and acts as a thermal buffer preventing the underlaying permafrost from losing energy to the cold active layer (Connon et al., 2018), an over-winter process essential for sustaining permafrost. Talik formation is therefore a tipping point, and usually leads to irreversible permafrost degradation (Jin et al., 2006; Lawrence et al., 2012; Devoie et al., 2019). Furthermore, a talik allows for two-sided thawing (Woo, 2012, p. 196), facilitating expedited active layer thaw during spring and early summer. Accurate predictions of permafrost and active layer thaw rates are dependent on the ice content of the ground, the presence, and patterns of talik formation, and heat fluxes through thawed, frozen, and partially frozen soils (Camill, 2005; Günther et al., 2015; Devoie et al., 2021). The thermal definition of permafrost insufficiently captures the energetics of permafrost systems, where (for instance) unfrozen soils at −2 °C can release more energy to their surroundings than frozen soils at 0 °C (Nicolsky and Romanovsky, 2018).

2.3. Soil state: field measurements, numerical modelling, and their agreement

There are currently three dominant field techniques for monitoring the state of the subsurface in permafrost regions (though others exist): temperature measurement using thermistors, approximate ice content measurement using a frost probe, and thermodynamic state using a thaw tube. Sites where continuous data is required use datalogging temperature sensors (e.g. thermistors, thermocouples etc.) to monitor the thermal state of the subsurface (Farquharson et al., 2022; Jin et al., 2006; Burn, 1998). This monitoring technique easily reports the top of the permafrost (0 °C) but cannot yield information regarding the phase of pore water in the active layer, talik, or permafrost. In contrast, when spatially distributed measurements are sought, a frost probe is the method of choice (a graduated steel rod inserted in the ground at the end of the thaw season until the point of refusal) (Camill, 2005; Mutter and Phillips, 2012; Sjöberg et al., 2012; Johansson et al., 2013; Jean and Payette, 2014). Measurement of active layer thickness by this method implicitly assumes, often erroneously, that the entire thickness of ground above the permafrost re-freezes in the winter, although re-freeze depths are rarely reported or measured (Connon et al., 2018). This method is insensitive to temperature, and likely reports the top of the permafrost well below the 0 °C isotherm where there is little to no ice content impeding the graduated rod. Neither of these methods report the depth of refreeze, leading to the use of frost tubes. Frost tubes were developed to simultaneously capture the evolution of multiple fronts in the active layer and the permafrost during thaw and freezing (Mackay, 1973). This device relies on the difference in optical properties between frozen and thawed water (in some cases with a dissolved indicator dye e.g. methylene blue) to monitor the movement of freeze and thaw fronts. Though this method has been validated for freezing, the thawing process is over-estimated potentially due to the distinct thermal properties, pore scale effects, and solute presence in the thaw tube compared to the adjacent soil (Iwata et al., 2012). Concerningly, data from all measurement techniques are often pooled in compilations of active layer thickness, and are based on the assumption that they are equivalent. This practice can lead to errors in estimating the both the thermal and physical state of the ground.

In field studies, permafrost thaw is often interpreted as 'active layer thickening' (Jia et al., 2017; Strand et al., 2021). For example the Circumpolar Active Layer Monitoring Program (CALM) has measured a systematically increasing depth to permafrost across the permafrost domain (Hinkel and Nelson, 2003). Though this interpretation is largely accurate in regions of cold, continuous permafrost (which behave according to Fig. 2a), in areas where permafrost is relatively warm and degrading, greater depth to permafrost is unlikely the result of active layer thickening (i.e. greater depth of seasonal freezing and thawing), and more likely indicative of talik formation and growth as indicated in Fig. 2b (ACGR, 1988). Though there are challenges associated with measuring the active layer thickness in areas where this layer does not refreeze to the top of the permafrost (Burn, 1998), the original definitions of the active layer in the literature are consistent, and identify incomplete refreeze as likely in discontinuous permafrost (Muller, 1947; ACGR, 1988). In such cases, locating the base of the active layer, while not trivial, is key to assessing water and energy balances, and to the numerical representation of permafrost systems in earth system models.

A freeze/thaw model is concerned with the enthalpy of the permafrost system – the combination of the sensible heat and latent heat as indicated by ground temperature and ice content respectively, where a vast majority of the energy is consumed by latent heat (Rühaak et al., 2015). Physical models rely on an SFCC to represent the freeze/thaw process, but the SFCC is often synthetic and/or based on data that are unrepresentative of the studied system, adding to the frequent misrepresentation of energy content in systems near the freezing point (Romanovsky and Osterkamp, 2000; Kurylyk et al., 2014; Lamontagne-Hallé et al., 2020; Devoie et al., 2022a, 2022b). The phase dependence of freeze-thaw models also poses serious challenges when validating them against field data.

There are three pitfalls when validating models against spatially distributed data collected using frost probes. First, the frost probes report the depth to refusal (Hinkel and Nelson, 2003). This 'hardness' value is dependent on the force applied, soil texture, and soil saturation, and likely does not align with the zero-degree isotherm, but rather some elevated ice content which is sufficient to withstand the force applied. This method is also challenging in unconsolidated soils with gravel and/or rock fragments. Second, validation data collected using frost probes assumes complete re-freezing of the active layer over winter (Brown et al., 2008). If instead the layer includes a talik, a model is unable to reproduce the over-reported active layer depths without significant and unrealistic changes to the surface energy balance. Third, it is assumed that the active layer refreezes in a saturated or near-saturated state. If the active layer is dry, or contains relatively dry pockets, it will offer less resistance to frost probing when it is thawing than an active layer (or permafrost) frozen in the saturated state, yielding over-estimated thaw depths. In some rare cases, temporal frost probe data is available throughout the thaw season (reporting thaw of the active layer) (Connon et al., 2018). In these cases, models may perform well in the thaw period (i.e. April to June), but once the thaw depth reaches the talik, the validation data shows an abrupt increase in the depth to refusal not captured by the model (Connon et al., 2018). Though continuous temperature data provides an easier comparison for freeze/thaw models, if the SFCC of the system is not represented accurately it is easy to misrepresent the ice content of the system while accurately capturing the ground temperature (Romanovsky and Osterkamp, 2000; Devoie et al., 2022b). Although active layer thickening is widely reported in the literature, such claims should be taken with caution, especially where talik layers may be present, and especially where data on the depth of refreeze is omitted. Best practices should include reporting the phase of pore water as well as the presence of a talik layer separating the active layer from the underlying permafrost.

2.4. Soil permeability: winter quiescence, permeable permafrost, and hydrologic function

Hydrologically speaking, permafrost regions have been generally assumed to be quiescent over winter (Woo, 2012, p. 163) However, SFCCs predict non-negligible unfrozen water content is in sub-zero (cryotic) soils, especially in the range of −2 °C to 0 °C (Koopmans and Miller, 1966). Though ice content is likely to limit the vertical movement of water through the active layer, 'warm' permafrost can contain little to no frozen pore water, allowing it to convey water laterally, even at sub-zero temperatures (Kleinberg and Griffin, 2005). This can lead to positive feedback where flowing water transfers additional advective energy to the permafrost (Devoie et al., 2021). Even near the base of the active layer, at the ice nucleation temperature, the pore water is liquid (ACGR, 1988). This is thought to be one of the drivers of the reported increases in baseflow in permafrost regions, shown in Fig. 3.

The increase in baseflow is also thought to be driven by slower active layer refreeze due to warmer winter conditions and deeper snow in the early snow-covered period (Boike et al., 1998; Evans et al., 2020), increased connectivity between suprapermafrost and subpermafrost flow paths due to permafrost thaw (McKenzie and Voss, 2013; Evans et al., 2020), and the increased prevalence of taliks (Connon et al., 2018; Farquharson et al., 2022). Taliks either store liquid water (and energy) within a depression surrounded by permafrost on all sides and the active layer from above, or convey water, allowing for increased subsurface hydrological connectivity (Brutsaert and Hiyama, 2012; Quinton and Baltzer, 2013; Devoie et al., 2021). Taliks have been extensively documented in permafrost environments such that the ACGR (1988) notes, "In the zone of continuous permafrost [the active layer] generally reaches the permafrost table. In the zone of discontinuous it often does not". Climate warming is rapidly extending the discontinuous permafrost region into what was previously the continuous region, increasing the prevalence and therefore importance of taliks (Zhang et al., 2006; Walvoord and Kurylyk, 2016; Meredith et al., 2019). Therefore, in areas of discontinuous permafrost, a measurement from the ground surface to the top of the permafrost should be assumed to be inclusive of the active layer and a talik, unless there is evidence that the ground freezes to the top of permafrost each winter. The observed increases of over-winter flow and occurrence of taliks, and the growing evidence of permeable, partially frozen soils, collectively challenge the assumption that permafrost acts as an impermeable barrier capable of containing water and soluble contaminants (Chuvilin et al., 2016; Kokelj et al., 2010; Walvoord and Kurylyk, 2016). The assumption that a permafrost system is composed of an active layer directly atop permafrost and that both active layer and permafrost contain a negligible amount of unfrozen pore water, does not match field observations in regions of thawing permafrost.

2.5. Unfrozen permafrost: a "hotspot" for microbial activity?

All known life on Earth requires liquid water for metabolic activity, even at below-zero temperatures (McKay, 2014). Cryophilic

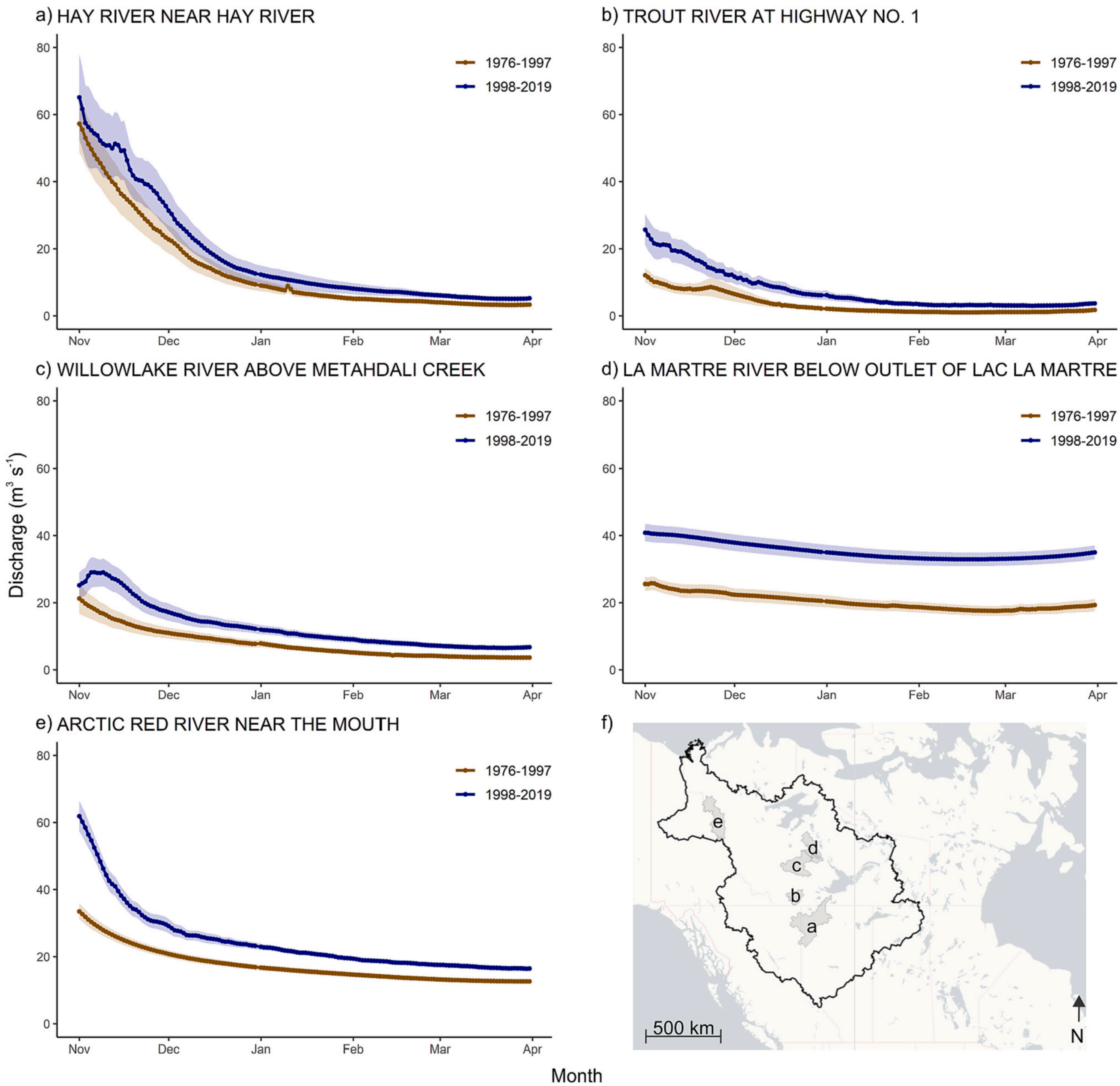

Fig. 3. Composite hydrographs depicting increases in winter baseflow in the Northwest Territories, Canada between 1976 and 2019 for and a) Hay River (48,200 km^2); b) Arctic Red River (18,800 km^2); c) La Martre River below outlet of Lac la Martre (13,900 km^2); d) Willowlake River above Metahdali Creek (20,200 km^2); and e) Trout River at Highway No. 1 (9270 km^2). Locations of each shown in f). Error bands indicate standard error. All gauges are operated by the Water Survey of Canada.

microorganisms are psychrophiles (cold-loving) extremophiles that are specifically capable of cell division at subzero temperatures (Goordial, 2021; Raymond-Bouchard et al., 2018). Cryophilic microorganisms possess multiple genomic, proteomic, and cell membrane adaptations to allow these organisms to maintain cellular structure and function at low temperatures (Bakermans et al., 2009; Feller and Gerday, 2003; Goordial et al., 2016b; Mackelprang et al., 2017; Raymond-Bouchard et al., 2018). While temperature drives rates of cryophile metabolic activity, with low temperature correlated with slower metabolism, the primary constraint for the limit of microbial life at low temperature is availability of liquid water, with some suggesting that there is no temperature limit for metabolically active life so long as sufficient liquid water is available (Goordial et al., 2013; Price and Sowers, 2004). Access to liquid water by cryophilic microorganisms is essential to allow for diffusion across cellular membranes, and to transport molecules into the cell and waste products out of the cell. In theory, while not thick enough to allow cellular motility, even a micrometer thick film of unfrozen water could be sufficient to sustain a cell at subzero temperatures through mobility of unfrozen water with required energy sources (Anderson, 1967; Goordial et al., 2013; Zhang et al., 2023).

As soils undergo the freezing process, the formation of crystalline ice excludes not only solutes, but also potentially cryophilic organisms, concentrating them in the residual unfrozen water content. This process has been well documented to occur in brine veins within sea ice (Junge et al., 2004), but is methodologically difficult to directly observe in permafrost. Supporting the co-location of microorganisms in briney, unfrozen water within frozen soils, is the observation that permafrost microorganisms capable of growth at subzero temperatures are nearly ubiquitously halophilic or halotolerant (salt loving/salt tolerant) (Goordial et al., 2013), or that the genomes of cold adapted organisms contain multiple adaptations to osmotic stress (Goordial et al., 2016b; Mykytczuk et al., 2013; Raymond-Bouchard et al., 2017; Raymond-Bouchard and Whyte, 2017; Raymond-Bouchard et al., 2018). For example, Planococcus halocryophilus Or1 is able to undergo cellular division at temperatures as low as −15 °C, and is tolerant of salt concentrations of 18 % NaCl (Mykytczuk et al., 2013). Salt concentrations over 5 % are inhibitory to most soil microorganisms. While the lowest observed temperature to date for cellular division by a microorganism in the lab is −15 °C, non-replicative metabolic activity such as cellular respiration can be observed at much lower temperatures in cryophilic microorganisms across broad taxonomic groups, putatively down to −40 °C (Goordial et al., 2013). Further, cells can persist in permafrost on long timescales by exerting minimal amounts of energy solely to remain viable in a state of "maintenance" (Burkert et al., 2019; Price and Sowers, 2004). However, cell membranes may be pierced by the formation of ice crystals causing cell death, and as a result water phase changes even at sub-zero temperatures in soils can mediate permafrost microbial ecology.

Current studies of microbial activity below 0 °C are often performed in a lab setting and use solutes to lower the freezing point of nutrient media to facilitate cryophilic cell cultures, but results align with in-situ measurements and bulk incubations of environmental samples (Jansson and Taş, 2014). Microbial activity in permafrost samples at subzero temperatures has been clearly demonstrated in Arctic, Antarctic and alpine settings. Notably, the only setting in which permafrost microbial activity at subzero temperatures has not been observed when assayed, is in dry permafrost from an extremely arid, high elevation McMurdo Dry Valley called University Valley. Due to its elevation and distance from the coast, University Valley dry permafrost is thought not to contain enough soil solutes to support unfrozen water content that would be suitable for active microbial life for more than hours annually (Goordial et al., 2016a; Marinova et al., 2022). Liquid water content is a clear driver of microbial activity, and thus a driver of quantity and rates of carbon and nutrient cycling in the subsurface where there is a high degree of spatial heterogeneity. More detailed soil data including unfrozen water content is critically needed to appropriately translate studies from a lab setting to a meaningful, spatially distributed scale (Jansson and Taş, 2014).

3. Conclusions and recommendations

Though permafrost is defined thermally, to understand the function of warming permafrost systems, it is critical to report not only the subsurface temperature but also the total water content, phase of the pore water, and associated ice content dependent mechanical properties. The phase of soil pore water defines the structural properties of soils, their permeability, and their total energy content. Currently there is a mismatch between the measurement techniques used to delineate permafrost and the methods used to model it, making predictions of thaw and thaw-related processes unnecessarily complex and uncertain. While it is thought that the active layer typically extends to the top of permafrost, and permafrost is typically frozen, ignoring the (surprisingly common) exceptions to these typical cases can lead to gross mischaracterization of permafrost systems and their function, including a misrepresentation of biotic and microbial communities. As such, we recommend that increased attention be given to the pore water phase of permafrost systems.

Data availability1

SFCC data is available in an open-source repository: doi:https://doi.org/10.5281/zenodo.5592825, while streamflow data can be freely accessed from the Government of Canada: https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html.

CRediT authorship contribution statement

É. Devoie: Conceptualization, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft. **R.F. Connon:** Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **R. Beddoe:** Writing – review & editing. **J. Goordial:** Writing – review & editing. **W.L. Quinton:** Conceptualization, Writing – review & editing. **J.R. Craig:** Conceptualization, Writing – review & editing.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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