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RESEARCH ARTICLE

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Characterization of Preferential Flow Occurrence During Freeze-Thaw Cycles



Key Points:

- Preferential flow (PF) leads to more efficient and accelerated energy transfer within frozen soils
- Preferential flow in frozen soils can be effectively identified by monitoring soil temperature changes at various depths
- Complementary use of soil temperature and moisture data reveals PF mechanisms across freeze-thaw cycles

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Preferential flow (PF) critically influences water and energy dynamics in frozen soils, yet its quantification and mechanisms remain poorly understood due to observational challenges. This study proposes a novel method to identify PF by analyzing soil temperature response times across depths. The method detects thermal anomalies—such as earlier or synchronized temperature peaks across depths—indicate rapid, advective heat transfer driven by PF and phase-change latent heat. We conducted our investigation in the Qilian Mountain areas using a network of soil temperature stations. Our findings reveal that PF significantly enhances magnitude and speed of energy transfer to deeper soil. Furthermore, the frequency of PF varies significantly across the partially frozen, frozen and partially thawing phases, as well as across different sites and depths, driven by shifts soil properties and meteorological forcing. Using random forest analysis, we identified key spatial drivers related to soil pore structure: soil organic carbon (partially frozen phase), residual soil moisture (frozen phase), and wilting point (partially thawed phase). Furthermore, classification and regression tree analysis revealed that the snowmelt rates and maximum near-surface (5 cm) soil temperatures are the primary temporal drivers of PF. Our study demonstrates that PF can be effectively identified by analyzing soil temperatures at various depths. By utilizing temperature-based detection during the frozen phase and moisture monitoring in the unfrozen phase, we can better correlate PF with soil hydrothermal conditions, ultimately elucidating the complex mechanisms governing water and energy dynamics during the freeze-thaw cycle.

Plain Language Summary In frozen soils, water can move through macropores, a process called “preferential flow (PF).” This type of water movement is important for transferring water and energy in frozen soil. However, current methods for identifying PF are not effective in frozen soil, making it difficult to understand its mechanisms and impact on water movement and energy transfer. To address this gap, we developed a new method to identify PF in frozen soil by measuring soil temperature changes at different depths. Our measurements are based on a observation network in the Qilian Mountains, Northwest China. Our findings reveal that PF significantly increases the speed and quantity of energy transferred to deeper soil. We also observed that the frequency of PF varies depending on the phase of freezing and thawing, location, and soil depth. We found that the characteristics of the pore structure as well as the snowmelt and maximum near-surface soil temperatures are the main factors influencing the occurrence of PF in frozen soils. Our study demonstrates that using temperature data during the frozen period and moisture data during the unfrozen period provides a comprehensive understanding of how PF impacts the soil hydrothermal state as well as the characteristics of PF during freeze-thaw cycles.

1. Introduction

More than 50% of the upper soils in the Northern Hemisphere experience seasonal or perennial freezing (Zhang et al., 2008), and preferential flow (PF) is known to significantly contribute to snowmelt infiltration in frozen soil (Espeby, 1990; French & Binley, 2004; Mohammed et al., 2019; Stähli, 2017; Stähli et al., 1996, 2004). This is because the presence of ice at low soil temperatures greatly reduces the hydraulic conductivity of the matrix in frozen soils (Ming et al., 2020; Watanabe & Flury, 2008), whereas the hydraulic conductivity of PF pathways, such as root holes and cracks, remains relatively unaffected (Demand, Selker, & Weiler, 2019; Espeby, 1990; Hu et al., 2023). This allows water to bypass some of the matrix (Flury et al., 1994) and move rapidly through the frozen soil. In the context of climate change, the Tibetan Plateau is projected to become warmer and wetter,

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leading to increased water supply to PF pathways and an associated decrease in surface runoff (Lei & Yang, 2017; Zhang, Nan, et al., 2021). This will have a significant impact on local ecohydrology. However, research on the effects of PF on water movement and energy transfer in frozen soils is limited, and the mechanisms driving PF under these conditions are poorly understood.

Current research on PF primarily focuses on the non-frozen period (Demand, Blume, & Weiler, 2019; Kang et al., 2023; Wickenkamp et al., 2016), with limited observational data and methodologies to investigate PF in frozen soil (Allaire et al., 2009; Demand, Selker, & Weiler, 2019). Directly quantifying PF processes in frozen soil through soil moisture (SM) observations poses significant challenges. This is due to the necessity of accounting for both energy and mass exchanges, which must include the contributions from phase changes of water (Mohammed et al., 2018; Walvoord & Kurylyk, 2016). Consequently, accurately determining the timing of SM changes in frozen soil cannot be achieved solely through the monitoring of liquid SM.

Most methods for monitoring SM at the point scale rely on electromagnetic (EM) techniques, such as time domain reflectometry (Robinson et al., 2003), time domain transmission (Blonquist et al., 2005), capacitance sensors (Kojima et al., 2016) and impedance sensors (Gaskin & Miller, 1996; Ojo et al., 2015). All these sensors rely on the strong dependency of the soil dielectric permittivity on the (liquid) SM content and can thus only determine the liquid (unfrozen) SM content. The soil dielectric permittivity is sensitive to temperature changes, in particular the phase transition from water to ice is associated with a strong decrease in the soil dielectric permittivity because of the much lower dielectric permittivity of frozen water (Bogena et al., 2017; He & Dyck, 2013). As a result, accurately measuring water content in frozen soils remains a challenge. However, water flow in frozen soil is frequently accompanied by energy transfer. Consequently, monitoring soil temperature variations provides a potential means to obtain information on (preferential) moisture movement (Moroizumi & Horino, 2002).

Mechanistic studies of PF in frozen soil have largely relied on small-scale indoor or field experiments using a wide variety of experimental approaches. For instance, Espeby (1990) demonstrated the existence of PF in seasonal frozen soil through isotopic and hydrochemical analysis. Meanwhile, Watanabe et al. (2012) evaluated the impact of initial SM on infiltration rates of frozen soil in indoor soil-column experiments with dynamically controlled boundary conditions. Sprinkling experiments have also been employed to investigate PF pathways in seasonal frozen soil (Stähli et al., 2004). Furthermore, Demand, Selker, and Weiler (2019) combined sprinkling experiments with ground-based infrared thermography to explore how the spatial distribution of frozen soil influences PF. Geophysical methods like electrical resistivity tomography have also been used for observing PF in seasonal frozen soil (French & Binley, 2004). However, none of these experimental methods can continuously observe PF in the field over extended periods (Guo & Lin, 2018). Consequently, the effect of varying water supply and initial SM content on the occurrence of PF remains difficult to investigate (Kang et al., 2023; Wickenkamp et al., 2016). In addition, sprinkling experiments and isotope tracing introduce chemical components to the snowpack, which alters the natural hydrothermal conditions and causes concerns about the extent to which such experiments reflect actual flow and transport processes in frozen soil (Cochand et al., 2019; M. Yang et al., 2019; Y. Yang et al., 2019).

It is widely acknowledged that pre-freezing SM, rate of snowmelt, macropore characteristics, and the extent of the frozen part of the soil are primary factors influencing the occurrence of PF in frozen soil (Demand, Selker, & Weiler, 2019; Mohammed et al., 2019, 2021; Watanabe & Flury, 2008; Watanabe & Kugisaki, 2017). However, the coupled process of water movement and heat transfer makes the hydrodynamics of PF very complex. For instance, pore connectivity is affected by ice content, and the refreezing and thawing of infiltrating water alters the hydraulic conductivity (Mohammed et al., 2018), leading to differences in the pathways and controlling factors of PF at different stages of the freeze-thaw cycle. Due to the limitations with the observation of PF in frozen soil, current studies are unable to determine the effects of freezing and thawing of water on PF occurrence through long-term observations (Demand, Blume, & Weiler, 2019; Watanabe et al., 2012). Consequently, there is a lack of understanding regarding the factors influencing PF at different stages of the freeze-thaw cycle under field conditions.

Soil moisture serves as a significant carrier of soil heat, exerting a substantial influence on soil temperature (An et al., 2017; Tao et al., 2017). This effect is particularly pronounced during the freezing period, where even minor water movement can induce notable changes in soil temperature due to the higher specific heat capacity of water compared to soil (Moroizumi & Horino, 2002). The latent heat release and uptake during phase changes, coupled with this contrast in heat capacity, make soil temperature a highly responsive indicator of water dynamics in

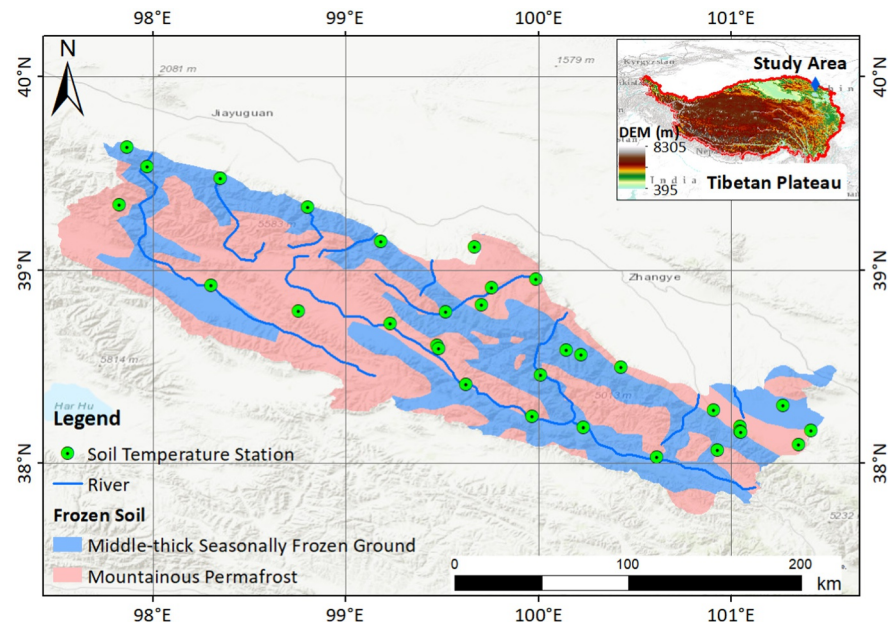


Figure 1. Frozen soil types (Ran et al., 2012) and distribution of measurement stations within the study area.

freezing soils (An et al., 2017; Ehrhardt & Gerke, 2022; Tao et al., 2017). Furthermore, the measurement principle of soil temperature is straightforward, with stable operation and minimal susceptibility to external influences, suggesting significant potential for identifying PF characteristics in frozen soil by monitoring soil temperature changes (Evelt et al., 2006). Moreover, several commercially available SM sensors are additionally equipped with temperature sensors, facilitating the prospect of unified PF identification during frozen and non-frozen periods.

Despite the significant impact of SM changes on energy transfer in frozen soil, current research predominantly focuses on the influence of PF on moisture dynamics and the effects on energy transfer are often not considered (Demand, Selker, & Weiler, 2019; Watanabe & Kugisaki, 2017). While many studies recognize the close relationship between moisture and energy in frozen soil and use numerical models of coupled mass and energy transport to analyze the hydrothermal changes (Mohammed et al., 2018), they typically only consider the impact of PF on hydrological processes such as runoff generation, infiltration, and groundwater recharge (Larsbo et al., 2019; Mohammed et al., 2019, 2021), overlooking its advective contribution to the soil thermal regime. This omission is critical because moisture transport during thawing significantly alters soil volumetric thermal properties and heat fluxes, ultimately dictating the freeze-thaw depth (Carey & Woo, 2013; Chen et al., 2023; Patton et al., 2021).

To investigate the occurrence and impact of PF on the hydrothermal characteristics of frozen soil, this study uses a network of soil temperature and SM observations in the seasonal frozen soil zone of the upper reaches of the Heihe River Basin in Northwestern China. The primary objectives of this study are as follows: (a) to analyze the effects of PF on water movement and energy transfer in frozen soils, (b) to investigate the spatial and temporal influences on PF during freezing periods, and (c) to examine the similarities and differences in the mechanisms of PF occurrence during different phases of the freezing periods.

2. Data and Methods

2.1. Study Area

This study relies on a data set of SM and temperature observations at 32 stations distributed across seasonal frozen soil zones in a complex landscape with varying elevation and soil properties (Tian et al., 2023). The monitoring network is located in the upper reaches of the Heihe River in the Qilian Mountains region (97°29′–101°32′E, 37°43′–39°39′N) (Figure 1) on the northeastern margin of the Tibetan Plateau. The altitude within the study area ranges from 1700 to 5,600 m above sea level. The hydrometeorological characteristics vary across the study site. The western region is dominated by mid-latitude westerly winds, while the eastern region is influenced by the south-

west monsoon and the south-east Asian monsoon (Che et al., 2019). Mean annual temperature in the region ranges from -3 to 7°C , mean annual precipitation ranges from 200 to 700 mm, and about 18% of the precipitation is snow (Geng et al., 2014; Wang et al., 2023). Temporary snow covers regularly occur below 2,700 m. Between 2,700 and 3,400 m, a patchy snow cover is found and a perennial snowpack exists above 3,400 m (Bi et al., 2015). Frozen soil also occurs above 3,600 m (about 52% of the study area), whereas seasonally frozen ground occurs below 3,600 m (Figure 1) (Hu, Wu, et al., 2022; Ran et al., 2012).

2.2. Data

2.2.1. Soil Moisture and Temperature Observation Network

The SM and temperature stations cover all elevation zones, soil types, and vegetation types in the upper Heihe River (Tian et al., 2023). At each station, five 5TE sensors (METER Group Inc., USA) were installed at depths of 5, 15, 25, 40, and 60 cm, respectively. The sensors have a 30 min temporal resolution with a sample volume of around $300\text{--}715\text{ cm}^3$ (Cobos & Chambers, 2010). The study period runs from January 2014 to December 2019. To avoid the impact of data quality on subsequent analyses, we removed outliers (e.g., SM values outside the 0 vol.% to 90 vol.% range and soil temperatures outside the $-40\text{--}60^{\circ}\text{C}$ range). To correct for the temperature dependence of the dielectric sensors used to measure SM, a temperature correction was applied to the raw SM readings (Saito et al., 2013). The temperature correction procedure consists of the following steps:

1. Selecting sequences of SM and temperature data corresponding to days with no rainfall and a daily temperature range exceeding 10°C .
2. Calculating the slope $\frac{dSM_p}{dT}$ representing the rate of change of the SM reading with temperature using Equation 1:

$$\frac{dSM_p}{dT} = \frac{SM_{p,\max} - SM_{p,\min}}{ST_{\max} - ST_{\min}} \quad (1)$$

where $SM_{p,\max}$ and $SM_{p,\min}$ are the maximum and minimum SM values from the sensor output for that day, and $ST_{\max}$ and $ST_{\min}$ are the maximum and minimum values of soil temperature for that day.

3. Establishing the relationship between the slope $\frac{dSM_p}{dT}$ and the daily average SM content through fitting.
4. Applying this relationship to the sensor output to obtain the temperature-corrected SM at the reference temperature SM_{corr} using:

$$SM_{\text{corr}} = SM_p - \left(\frac{dSM_p}{dT} \right) (T - T_{\text{ref}}) \quad (2)$$

where SM_p is the raw sensor reading, T is the measured temperature, and T_{ref} is reference temperature (20°C). For comprehensive details on the temperature-correction methodology, the reader is referred to Saito et al. (2013).

We focused on changes in SM and energy during soil freezing periods (days where the minimum temperature of at least one measurement depth is below 0°C). For this, the freeze-thaw state of the soil was categorized into four soil temperature states, namely partially frozen phase (from autumn to early winter, the minimum temperature of at least one sensor falls below 0°C), frozen phase (winter, days when minimum value of soil temperatures at all depths remains below 0°C), partially thawed phase (from late winter to early spring, the minimum temperature of at least one sensor rises above 0°C after frozen phase) (Hu, Li, et al., 2022; Mohammed et al., 2019), and thawed phase (i.e., summer, days when minimum value of soil temperatures at all depths remains above 0°C). Figure S1 in Supporting Information S1 illustrates the various phases during the freeze-thaw cycle for one station. It is important to note that the timing of each phase can vary due to the wide variety of conditions across the region as well as the year-to-year variability in temperature at the same sites.

Soil samples were collected concurrently with the sensor installation at each depth and used to determine bulk density (BD), saturated hydraulic conductivity (K_s), soil organic carbon (SOC) content, soil texture, and the parameters of the van Genuchten model for the SM retention curve (i.e., n , α , saturated SMs, and residual SM (SM_r)). In addition, we calculated the field capacity and the wilting point (WP) from the SM retention curve (Rawls et al., 1998). We refer to Tian et al. (2017) for more details on the soil analysis.

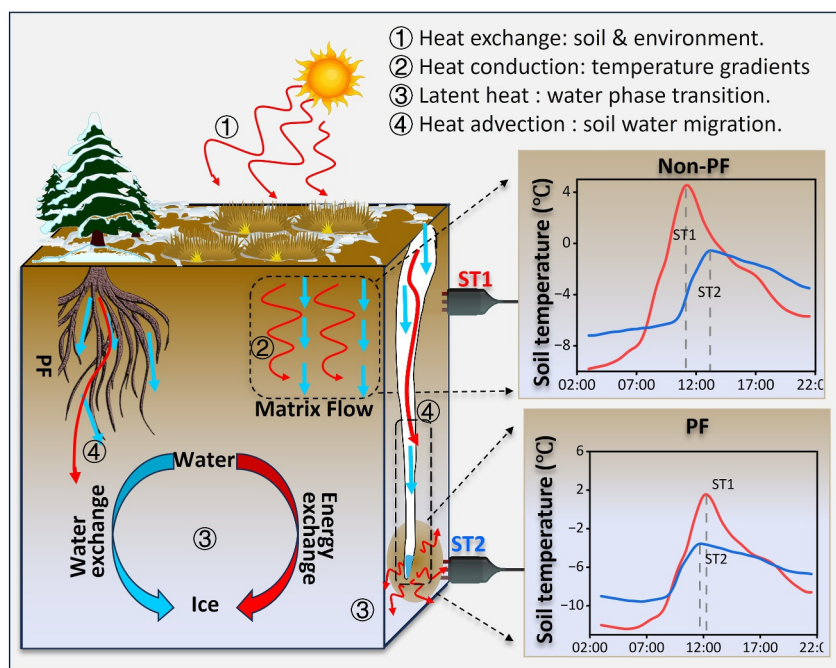


Figure 2. Conceptual diagram of water and energy transport for preferential flow (PF) and non-PF processes during freezing periods. The peak soil temperature at deeper measurement depths (ST2) occurs earlier than the peak soil temperature at shallower measurement depths (ST1) when PF occurs.

2.2.2. Meteorological and Snow Data

Due to budget constraints, we were not able to install ground-based weather stations at the temperature monitoring locations to observe snow depth and other meteorological variables. To analyze the influence of snow depth and meteorological variables on the occurrence of PF during freezing periods, we therefore extracted meteorological data from the China Meteorological Forcing Data set (CMFD). This is a reanalysis product with a temporal resolution of 3 hr and a spatial resolution of $0.1^\circ \times 0.1^\circ$ (He et al., 2020; Yang et al., 2010). Specifically, we extracted air temperature (AT), air pressure (Pres), specific humidity (Shum), downward shortwave radiation (Srad), downward longwave radiation (Lrad), and precipitation rate (Prec) for the study locations. Second, we obtained an independent daily snow depth data set with a spatial resolution of 0.25° (Hu et al., 2021). This data set was used to calculate the snow depth change rate (SDC)—defined as the difference in snow depth between two consecutive days—which serves as a proxy for water supply from snowmelt or accumulation.

2.3. Determination of PF During Freezing Periods

The transport of SM during freezing periods is accompanied by heat transfer due to phase changes (freezing and thawing) in water. The soil temperature change due to this heat transfer is large enough to be used to evaluate whether soil water is moving. Therefore, it is possible to determine the occurrence of PF by analyzing the changes in soil temperature at different depths.

Soil thermal dynamics are governed by four interdependent processes: (a) surface energy balance (solar radiation, atmospheric exchange), (b) conductive heat transfer along temperature gradients, (c) advective heat transport via water movement, and (d) latent heat flux during water phase transitions (Figure 2). The temperature of the topsoil undergoes periodic fluctuations owing to diurnal variations in solar radiation. During periods of intense solar radiation and increased soil surface temperature, energy is transferred from the surface to deeper soil. Conversely, during the night, the topsoil dissipates heat to the atmosphere, resulting in a decrease in soil temperature. During this nocturnal phase, energy predominantly moves from the subsoil toward the topsoil. Consequently, surface soil temperature exhibits greater variability compared to the subsoil (Hinzman et al., 1998; Schrott, 1991). In homogeneous soil conditions (i.e., no PF), both water and energy are uniformly transferred, with the energy and water taking some time to transfer, causing the peak of soil temperature to gradually lag with depth (see Figure 2).

According to the soil heat transfer equation, the change in soil temperature at any moment and depth can be determined using (Shao et al., 2006):

$$T(z, t) = T_A + A \exp\left(\frac{z}{d}\right) \sin\left(\omega t + \varphi + \frac{z}{d}\right) \quad (3)$$

where T is the soil temperature ($^{\circ}\text{C}$), t is the time (hr), z is the depth (cm), d is the damping depth (cm), ω is the angular frequency ($=2\pi/\tau$, h^{-1}), τ is the period (e.g., 24 hr), and φ is the phase constant. The damping depth can be obtained using:

$$d = \sqrt{\frac{\alpha \tau}{\pi}} \quad (4)$$

where α is the thermal diffusivity of soil ($\text{cm}^2 \text{hr}^{-1}$), calculated as:

$$\alpha = \frac{k}{\rho \times c_p} \quad (5)$$

where k is the thermal conductivity ($\text{W}/(\text{m K})$), c_p is the specific heat capacity ($\text{J}/(\text{kg K})$), and ρ is the density (kg/m^3). Together, $\rho \times c_p$ is also referred to as the volumetric heat capacity ($\text{J}/(\text{m}^3 \text{K})$). The time lag in soil heat transfer between two measurement depths (Δt) can be obtained from Equations 3 and 4 (Jury & Horton, 2004; Zheng et al., 2021, 2023):

$$\Delta t = \Delta z \sqrt{\frac{\tau}{4\pi\alpha}} \quad (6)$$

where Δz is the distance between the two soil temperature measurement depths. The thermal diffusivity of any soil is less than $21.6 \text{ cm}^2 \text{hr}^{-1}$, while ice exhibits substantially higher diffusivity (about $42.48 \text{ cm}^2 \text{hr}^{-1}$) (Arkhangelskaya & Lukyashchenko, 2018; Shao et al., 2006). Based on the thermal properties of the soil at our study sites, the theoretical conductive time lag between sensors exceeds 1.3 hr. This time lag is far beyond our soil temperature monitoring resolution of 30 min. Field observations confirm this progressive lag in our data set. Figure S2 in Supporting Information S1 shows that temperature peaks at 15 cm depth are consistently delayed by 0.5–2 hr relative to the peaks at 5 cm. The delay in peak timing at a depth of 25 cm exceeds 2 hr.

PF fundamentally reconfigures subsurface energy transport by enabling rapid advective transfer of water to depth, where subsequent refreezing releases significant latent heat. Due to the significantly higher specific heat capacity of water, even small amounts of water flow generate measurable thermal perturbations (Moroizumi & Horino, 2002; Tao et al., 2017). Critically, the limited interfacial contact between fast-flowing water of PF and the surrounding soil matrix minimizes conductive energy exchange (Demand, Selker, & Weiler, 2019), facilitating direct thermal energy delivery to deeper soil. This process manifests itself through two diagnostic thermal anomalies that violate the constraints derived for heat conduction in homogeneous media.

First, an inversion in peak temperature timing can be observed, where deeper soil layers exhibit earlier temperature peaks than the overlying layers (e.g., in Figure S3 in Supporting Information S1, the 15 cm peak precedes the 5 cm peak on Days 1–2). This “thermal short-circuit” effect occurs when warmer soil water rapidly traverses macropores and releases latent heat at depth during refreezing.

Second, quasi-simultaneous temperature peaks can be observed at adjacent depths within ≤ 0.5 hr (Figure S4 in Supporting Information S1). This is physically irreconcilable with either energy advection velocities (maximum $K_s = 7.71 \text{ cm/hr}$; > 1.3 hr when accounting for reduced hydraulic conductivity in frozen soil) or heat conduction velocities within the soil matrix (> 3.6 hr for $\Delta z = 10$ cm, as conduction velocity depends on soil properties and does not increase with temperature). Therefore, quasi-simultaneous temperature peaks at different depths also provide convincing evidence for PF.

Soil temperature simulations performed using Hydrus-1D for the same period (Figure S5 in Supporting Information S1) demonstrate the characteristic conductive lag in the absence of PF: the peak at 15 cm is delayed by 1 hr

Table 1

Total Days Across All Study Stations That Satisfied the Criteria for Each Identification Step During the Frozen Periods (2014–2019)

	Freeze-thaw	Soil temperature of first shallowest measurement depth is >0	PF			
			5–15 cm	15–25 cm	25–40 cm	40–60 cm
Partially Frozen	1,543	1,543	126	74	14	64
Frozen	19,413	5,212	278	254	82	249
Partially Thawed	3,700	3,698	203	141	24	126

relative to the peak at 5 cm, and the peak at 25 cm is delayed by 2 hr relative to the peak at 15 cm. The systematic deviation between the observed thermal anomaly and the model simulations that exclude PF pathways provides compelling evidence for PF dynamics during these events.

Based on these considerations, the determination of PF occurrence during freezing periods can be achieved through the following steps:

1. Identify the freezing periods by determining the days on which the soil temperature is below 0°C in at least one depth.
2. To mitigate the impact of instrumental noise on the results, remove the depths where the difference in soil temperature (i.e., the difference between the maximum and minimum values of soil temperature) is below a predefined threshold value (i.e., 0.1°C, the resolution of the temperature measured by the 5TE sensor) for each day.
3. Calculate the timing of the maximum soil temperature occurrence for the remaining dates.
4. Retain only the instances occurring during the freezing periods when the maximum value of soil temperature in the shallowest measurement depth (5 cm) exceeds 0°C. In the absence of snow depth observations and due to the limited spatial resolution of the snow depth data set (Hu et al., 2021), a soil temperature in the shallowest measurement depth of above 0°C is assumed to indicate the start of snowmelt or thawing weather (Teubner et al., 2015; Zhang, Yuan, et al., 2021). This interpretation is justified because during snow cover, near-surface soil temperature changes—particularly during the frozen-to-thawed transition—provide a clearer indicator of the energy input threshold triggering snowmelt than in-snow temperature variations (Espeby, 1990; French & Binley, 2004). This is because snow temperatures persist near 0°C for extended periods due to thermal insulation of snow and latent heat buffering during phase changes, whereas soil temperatures >0°C represent a relatively unambiguous signal of thermal state transition, strongly suggesting liquid water formation beneath the snowpack. This near-surface thaw provides the necessary liquid water input for PF occurrence.
5. Compare the timing of soil temperature maxima between two adjacent measurement depths. If the maximum soil temperature occurs earlier at the deeper measurement depths than at the shallow measurement depths, or if both measurement depths reach maximum temperatures at the same time, this indicates that PF occurred between these two depths on that specific day (Figure 2). This pairwise criterion is applied independently to all adjacent sensor pairs in the profile.

It is important to note that this method establishes a detection threshold based on thermal signal propagation. It is designed to identify PF events that are rapid enough to overcome conductive heat transfer and produce a clear thermal signature (peak-timing inversion or quasi-simultaneous temperature peaks). While this approach is expected to capture PF events with significant advective heat transport, it may not detect minor PF events with a correspondingly weaker impact on subsurface energy dynamics. This limitation is consistent with the study's objective to investigate PF events that substantially alter hydrothermal regimes in frozen soils. Consequently, the PF events identified and analyzed in this study represent those with a pronounced thermal—and thus hydrological—impact.

The above presented steps to identify days with PF occurrence during freezing periods were all performed automatically using MATLAB scripts. Table 1 summarizes the number of days where PF was identified at different depths during the freezing periods. Based on the identified PF events, we calculated two complementary frequency metrics for each site. First, the relative PF frequency was calculated for a given depth as the number of PF events at that depth divided by the total number of PF events across all monitoring depths at the same site. This metric illustrates the vertical distribution of PF activation. Second, the absolute PF frequency for each site was

calculated as the total number of PF events (across all depths) divided by the total number of snowmelt events, expressed as a percentage. This metric represents the overall likelihood of PF occurrence at the site scale during the monitoring period. Here, it is important to note that “PF frequency” refers to the proportion of monitored water input events (e.g., rainfall or snowmelt episodes) that exhibited evidence of PF, as detected by our thermal response method. It is a measure of how often PF pathways are activated, not a quantitative estimate of the fraction of total water volume moving through such pathways.

To describe the effect of PF on SM and energy during the freezing period, we defined three additional quantitative indicators: the change in liquid SM saturation per day (ΔS), the ratio of surface to deep energy transfer (RST), and the velocity of the energy transfer between the first (5 cm) and fifth (60 cm) measurement depths (EV_{1-5}). The change in liquid SM saturation (ΔS , %) was calculated using:

$$\Delta S_d = S_{d+1} - S_d \quad (7)$$

with

$$S_d = \frac{SM_{dc} - SM_r}{SM_s - SM_r} \times 100 \quad (8)$$

where S_d represents the liquid SM saturation at the moment of maximum soil temperature on day d (%), SM_{dc} represents the temperature-corrected value (see Section 2.2.1) of SM corresponding to the moment of maximum soil temperature on day d (vol.%), and SM_s and SM_r represent the saturated (vol.%) and residual water content (vol.%), respectively. The ratio of surface to deep energy transfer is the ratio of the amount of change in the subsurface soil temperature to the amount of change in the surface soil temperature (RST, %) and is calculated as:

$$RST = \frac{ST_{L,max} - ST_{L,min}}{ST_{1,max} - ST_{1,min}} \times 100 \quad (9)$$

where ST_L (°C) represents the temperature at different measurement depths (depths 2–5) and ST_1 (°C) represents the temperature at the shallowest measurement depth (5 cm), respectively. ST_{max} and ST_{min} are the maximum and minimum values of soil temperature at a given depth for each day (°C). Finally, the velocity of energy transfer between the shallowest (5 cm) and deepest (60 cm) measurement depths (EV_{1-5} , cm/hr) is calculated by:

$$EV_{1-5} = \frac{D_5 - D_1}{t_{5,max} - t_{1,max}} \quad (10)$$

where D_5 and D_1 are the soil depths of the shallowest and deepest measurement depths (cm), and $t_{5,max}$ and $t_{1,max}$ are the times (h) at which the maximum values of soil temperature occurred on each day at the shallowest and deepest measurement depth, respectively.

2.4. Methods of Analysis

2.4.1. Classification and Regression Trees

Classification and regression trees are statistical methods used to construct tree predictors that address regression and classification problems. Previous research has demonstrated that these methods can be applied to investigate patterns of PF occurrence (Kang et al., 2023). The classification and regression trees algorithm initially generates a maximally complex tree through exhaustive recursive partitioning. While this unpruned model achieves perfect training accuracy (0% error, Equation 11), it exhibits severe overfitting. To optimize generalization, we applied complexity-based pruning following Genauer and Poggi (2020), selecting tree complexity that minimized cross-validation error. This strategic simplification intentionally increased training errors while significantly improving validation performance.

Once the classification tree is established, it can easily predict variable types, that is, it is possible to determine whether it is a PF or not. Starting from the root of the “tree”, the conditions of each node are evaluated sequentially. If met, the process proceeds to the left node; otherwise, it goes to the right node. Following a series

of decisions, a unique path from the “root” to the “leaves” determines the variable type. The “rpart” package (Therneau & Atkinson, 2018) and the “rpart.plot” package (Milborrow, 2018) in R were used to construct the classification tree in this study.

To determine the conditions under which PF occurs, we constructed classification trees for different frozen periods. The response variable was whether PF occurred. Explanatory variables included SDC, surface soil energy condition ($STI_{\max}$ and $STI_{\min}$, maximum and minimum value of soil temperature in the shallowest measurement depth), and AT, as well as downward longwave ($Lrad$) and shortwave radiation ($Srad$). To ensure equal weighting of these factors across sites, we employed a z-score transformation to standardize each explanatory variable at each site (Wu et al., 2001). To assess the reliability of the classification tree, we randomly sampled data from two-thirds of the days to construct the tree and validated it using the remaining days. The error for the classification tree was quantified as follows:

$$err = \frac{1}{n} \sum_{i=1}^n 1_{Y_i \neq T(X_i)} \quad (11)$$

where n is the number of infiltration events, Y is the response variable, T is the constructed classification tree, X is the prediction variable, and $T(X)$ denotes the type of event predicted by the classification tree.

2.4.2. Random Forest

Random forest is a method relying on a collection of unpruned classification and regression trees. While individual trees exhibit some randomness, the “forest” encompasses a broad exploration of all possible trees, retaining the advantages of classification and regression trees while enhancing predictive performance (Therneau & Atkinson, 2018). The random forest approach can assess the importance of input variables on response variables, ranking their impact to aid variable selection. This variable importance (VI) is quantified as follows:

$$OOB \text{ error} = \frac{1}{n} \sum_{i=1}^n (Y_i - \hat{Y}_i)^2 \quad (12)$$

$$VI(X^j) = \frac{1}{q} \sum_{k=1}^q (\widetilde{OOB \text{ error}_k^j} - OOB \text{ error}_k) \quad (13)$$

where n is the number of samples, Y is the response variable, $\hat{Y}$ is the corresponding predicted value, X are the explanatory variables, q is the number of trees constructed, $OOB \text{ error}_k$ is the OOB error of tree k , $\widetilde{OOB \text{ error}_k^j}$ is the error of the tree k after perturbation of X^j after a random permutation of the values of variable X^j .

Genuer et al. (2010) introduced a variable selection method based on random forest (VSURF). This method automatically filters relevant variables from a large pool of candidates, without requiring the upfront specification of the number of variables. Moreover, VSURF distinguishes between two variable selection objectives: explanatory and predictive. The explanatory objective aims to select all variables significantly related to the response variable, even in the presence of multicollinearity. Conversely, the predictive objective focuses on identifying a subset of variables that effectively predict the response variable, minimizing the impact of multicollinearity. Typically, the subset of variables selected to meet the explanatory objective contains a larger number of highly correlated variables. In contrast, the subset of variables selected for the predictive objective usually consists of only a few weakly correlated variables. In this study, we use the VSURF method to identify the main spatial factors that control the occurrence of PF.

3. Results

3.1. Distributional Characteristics of PF

Figure 3 shows the relative frequency of PF occurrence at various depths throughout the three phases of the frozen period, that is, the ratio of the number of events with PF at a given depth to the total number of events with PF at all depths at that site. PF was not detected at more than half of the stations during each phase, which resulted in a

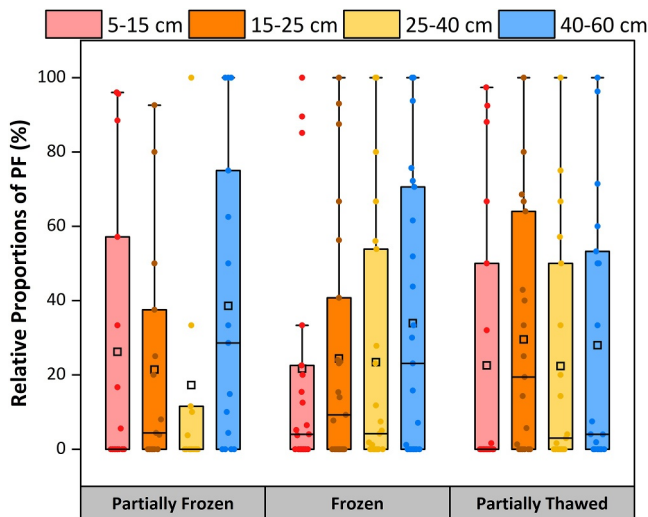


Figure 3. The relative frequency of preferential flow (PF) at different soil depths during the three phases of the freezing periods. The horizontal line in each box indicates the median value of the relative frequency of the PF (some boxes do not have the horizontal line because the median is 0%), the square indicates the mean value, the box indicates the interquartile spacing (25th and 75th), and the whisker ends indicate the fifth percentile and 95th percentile. The 5th percentile, 25th percentile, and median values are all 0, resulting in an overlap of these three percentiles, as PF events were detected in only a few of the stations at these monitored soil depths.

median relative frequency of PF of 0%. This pattern was particularly pronounced during the partially frozen phase and partially thawed phase (Figure 4). Across all phases, the median frequency of PF was higher at depths of 15–25 and 40–60 cm compared to depths of 5–15 and 25–40 cm (Figure 3). The highest relative frequency of PF was found at a depth of 40–60 cm during the partially frozen and frozen phases, while the depth of 15–25 cm showed the highest relative frequency of PF during the partially thawed phase (Figure 3). Furthermore, the frequency of PF exhibited considerable variation from site to site (the coefficients of variation from these sites are 1.85, 1.56, and 1.73 for different freezing periods, respectively) (Figure 4). In addition, the frozen phase exhibited the highest frequency of PF, followed by the partially thawed and partially frozen phases (Figure S6 in Supporting Information S1). However, the distribution of PF across different phases was similar among the sites. For instance, the frequency of PF at MG6, MG8, and S3 were consistently higher across all three phases. In contrast, the forest sites F1 to F3 exhibited low PF frequencies despite abundant root-associated macropores (Figure 4). This discrepancy stems primarily from methodological challenges in detecting PF during freezing periods at forested sites, as discussed in Section 4.3.

3.2. The Impacts of PF on Water and Energy Transfer

To evaluate the influence of PF on SM dynamics and energy transfer during the freezing periods, we conducted an analysis focusing on the changes in liquid SM saturation (ΔS , Figure 5) and the ratio of soil energy transfer (RST, Figure 6) per day. Across all phases, ΔS exhibited a gradual decrease with

increasing soil depth. However, we did not observe a discernible effect of PF occurrence on ΔS , and the median value of ΔS remained near 0% across most depths regardless of the presence or absence of PF derived from temperature changes (Figure 5).

In contrast, a significant impact of PF on the RST at different depths was observed, with the occurrence of PF causing the deeper soil to receive more energy (Figure 6). For instance, the median RST during days with PF was 82% between the first and the second measurement depth (5–15 cm) in the partially frozen phase, 76% in the frozen phase, and 77% in the partially thawed phase. In contrast, the median RST during the days without PF were only 44% (partially frozen phase), 38% (frozen phase), and 43% (partially thawed phase). The difference in median RST between periods with and without PF was 38% (partially frozen phase), 38% (partially thawed phase), and 34% (partially thawed phase) at depth of 5–15 cm, and –1% (partially thawed phase), 0% (partially thawed phase), and 7% (partially thawed phase) at depth of 5–50 cm. That is, the increase of energy transfer due to PF was more pronounced at shallow depths compared to deeper measurement depths (Figure 6). It is noteworthy that RST exceeded 100% for some soil depths on some days when PF occurred (Figure 6). This observation underscores the notion that PF introduces an additional source of energy into the soil system.

We conducted further analysis on the velocity of energy transfer from the shallowest (5 cm) to the deepest measurement depth (60 cm) (EV_{1-5} , Figure 7). We observed that EV_{1-5} on days with PF was consistently higher than on days without PF across all phases (Figure 7). Additionally, the increase in EV_{1-5} due to PF was particularly pronounced during the frozen and partially thawed phases. The median value of EV_{1-5} during periods with PF was 1.54 cm/hr higher than the median value of EV_{1-5} during periods without PF in the partially frozen phase, 5.75 cm/hr higher in the frozen phase, and 5 cm/hr higher in the partially thawed phase.

3.3. Spatial Controls on PF Occurrence

The significant spatial (Figures 3 and 4) and temporal variability (Figure 4 and Figure S2 in Supporting Information S1) observed in the PF occurrence across the study region underscore the heterogeneity of soil properties and meteorological factors, among other variables, at this broader scale. This variability also emphasizes the impact of small-scale spatial and temporal factors on water and energy dynamics within the soil. In the following, we will analyze the factors influencing PF during the three phases of the freezing period in more detail.

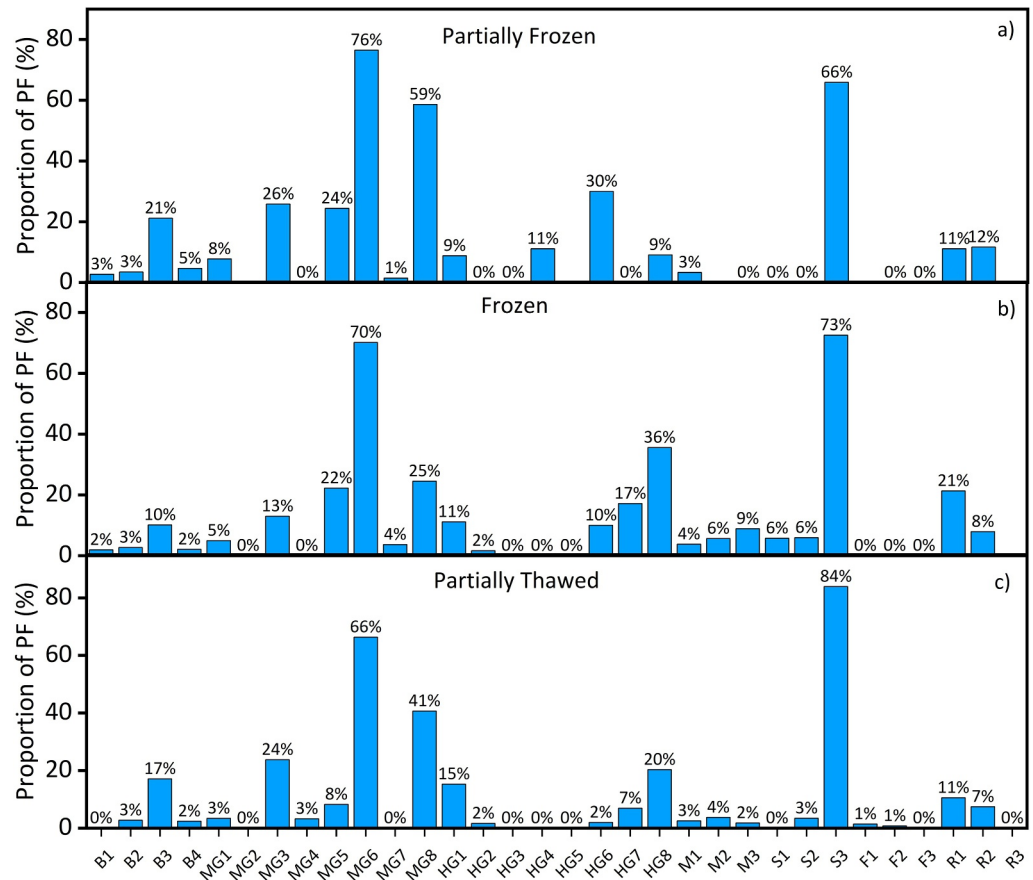


Figure 4. Frequency of preferential flow occurring at each site during the three phases of the freezing period (partially frozen phase (a), frozen phase (b), and partially thawed phase (c)). The abbreviations represent the land cover types at each station: Barren land (B), medium-coverage grassland (MG), high-coverage grassland (HG), meadow (M), shrub (S), forest (F), and rock (R).

Figure 8 presents Spearman's correlation coefficients between the frequency of PF occurrence and spatial factors, including soil properties, vegetation, topography, and multi-year average meteorological characteristics, for the partially frozen, frozen, and partially thawed phase, respectively. Overall, most spatial factors showed non-significant correlations with the frequency of PF occurrence. However, BD ($R = 0.7$), WP ($R = 0.4$), and Srad ($R = 0.5$) exhibited significant positive correlations and SOC ($R = -0.5$) exhibited significant negative correlation with the frequency of PF occurrence during the partially frozen phase. In the frozen phase, significant positive correlations were found with the frequency of PF occurrence during the non-frozen period (GSPF: $R = 0.5$), WP ($R = 0.4$), and snow depth (SD: $R = 0.4$). Similarly, during the partially thawed phase, BD ($R = 0.4$), WP ($R = 0.4$), Srad ($R = 0.4$), and SD ($R = 0.4$) displayed significant positive correlations with the frequency of PF occurrence.

We used the VSURF approach to identify the most influential spatial factors controlling the occurrence of PF during each phase (Figure 9). SOC emerged as the most important predictor variable during the partially frozen phase (the VI of SOC was greater than the other variables during this phase). However, for the other phases, no predictor variables could be discerned, suggesting that it was not feasible to analytically predict the frequency of PF occurrence using only a limited number of spatial factors. During the partially thawed and frozen phases, the most crucial spatial factors controlling the occurrence of PF were WP, and $SM_{r,n}$, respectively (Figure 9). Additionally, it is noteworthy that WP exerted a significant effect on the occurrence of PF in all phases.

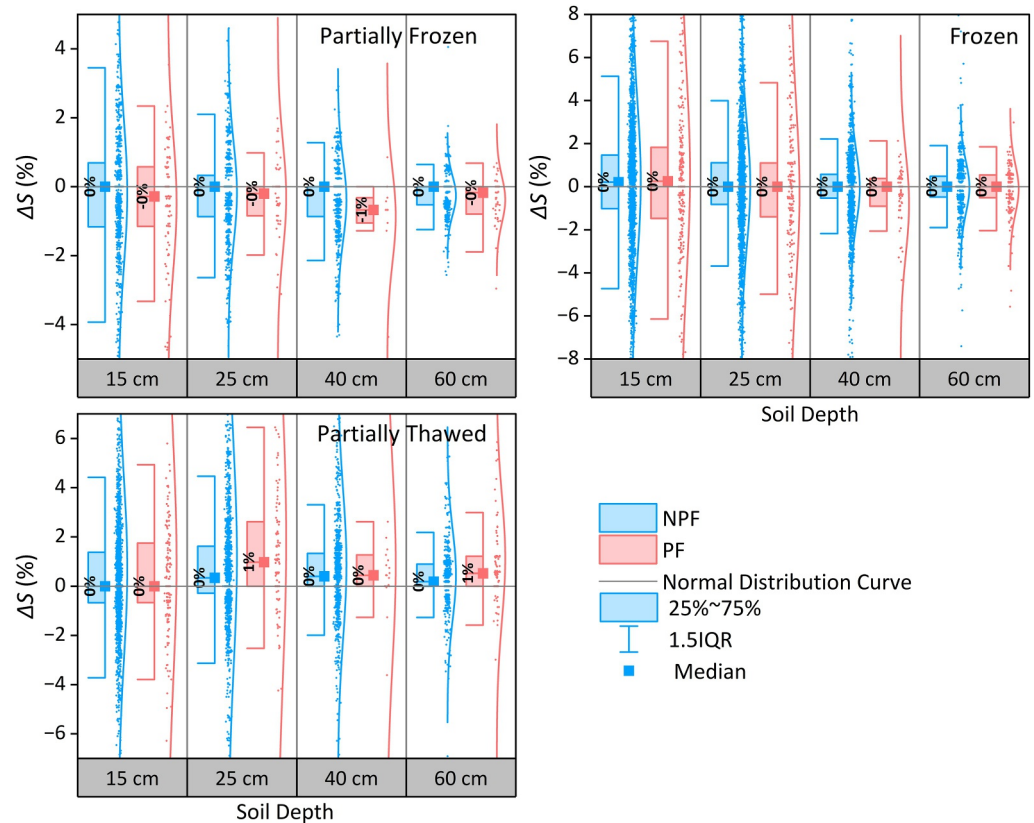


Figure 5. Changes in liquid soil moisture (SM) saturation (ΔS , Equation 7) at different soil depths on days with preferential flow (PF) and without PF (NPF) during the three phases of the freezing periods. The figure illustrates the change in liquid SM saturation between two depths; thus, it does not show changes in liquid SM saturation at the shallowest soil depth.

3.4. Temporal Controls on PF Occurrence

To investigate the specific control of energy and moisture conditions on the occurrence of PF, decision trees were constructed for each of the three phases. The classification error rates (distinguishing between PF and non-PF events) of the decision trees for the training and validation sets for each phase are presented in Table 2. The error rates (err, Equation 11) for all phases were less than 0.18, indicating that the conditions for the occurrence of PF can be reliably determined based on these decision trees.

Table 3 presents the importance of the explanatory variables in controlling the occurrence of PF. The occurrence of PF was primarily influenced by $ST1_{max}$ and SDC. SDC was the most important variable during the partially frozen and frozen phases, while $ST1_{max}$ was most significant during the partially thawed phase. During the partially frozen phase, PF primarily occurred when SDC was greater than -0.011 and less than 0.031 , with a probability of 76% (Figure 10). Additionally, PF occurred when SDC was greater than -0.011 and $ST1_{min}$ was greater than 0.87 , yielding a probability of 64% (Figure 10a). In all other scenarios, the probability of PF was less than 30%. During the frozen phase, PF events primarily occurred when the SDC was between -0.029 and -0.024 , resulting in an 84% probability of occurrence. PF was also likely when the SDC was greater than -0.02 with a probability of 73%, and when it ranges between 0.028 and 0.037 , with a probability of 71% (Figure 10b). In all other situations, the likelihood of PF occurrence was less than 30%. During the partially thawed phase, PF primarily occurred when the $ST1_{max}$ was less than -0.74 , with a probability of 39%, or when the SDC was between 0.023 and 0.053 , with a probability of 85% (Figure 11). In all other cases, the probability of PF was less than 20%. In summary, PF was more prone to occur in conditions characterized by smaller SDC (all phases), larger $ST1_{min}$ (partially frozen phase), and smaller $ST1_{max}$ (partially thawed phases).

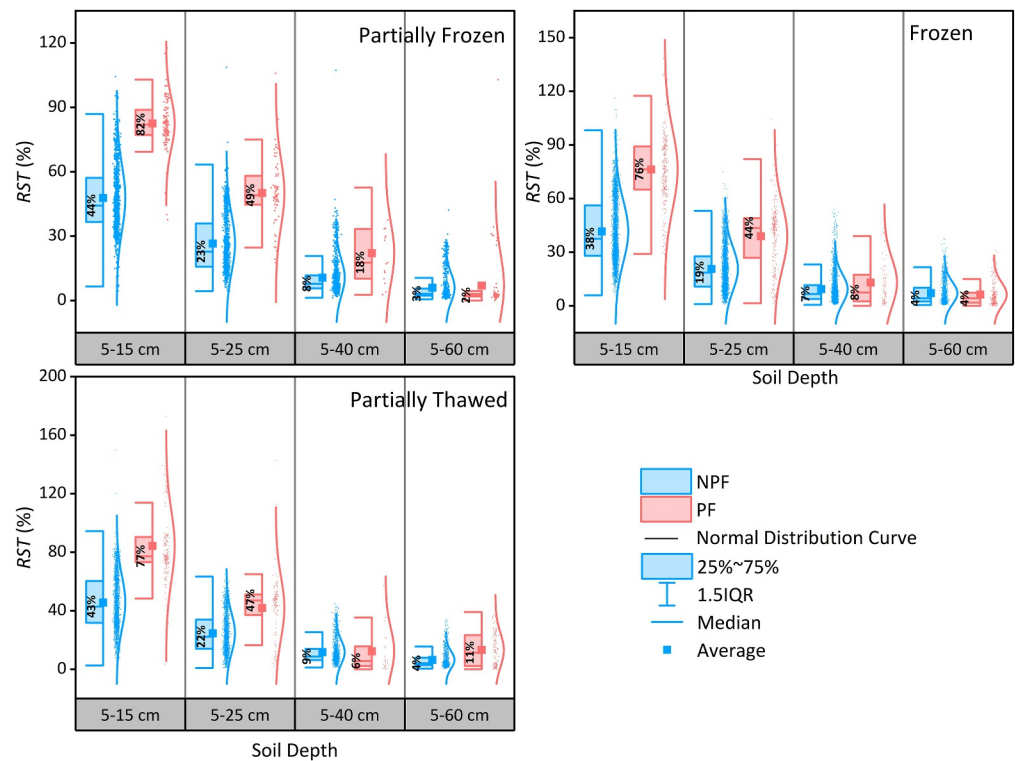


Figure 6. The ratio of subsurface soil temperature to surface soil temperature (5 cm) change (RST, Equation 9) on days with preferential flow (PF) and without PF (NPF) during the three phases of the freezing periods. This ratio is a proxy for the proportion of surface soil energy received by the deeper soil.

4. Discussion

4.1. Effect of PF on Energy and Liquid Soil Moisture in Frozen Soil

PF exerts a significant influence on water movement and energy transfer in frozen soil. During freezing periods, PF primarily affects energy transport (Figures 6 and 7) (Chen et al., 2020; Hu et al., 2023; Kane et al., 2001), whereas during the non-frozen period, it plays a more crucial role in water movement (Figure 12) (Guo & Lin, 2018; Kang et al., 2023; Wickenkamp et al., 2016). During periods of freezing, ice clogs the smaller soil pores and thus reduces the hydraulic conductivity of the soil matrix (Demand, Selker, & Weiler, 2019; Kane, 1980). Consequently, water movement is expected to occur predominantly through macropores. However, in this study, we did not observe a significant effect of PF on water movement (Figure 5). Regardless of PF occurrence, changes in liquid SM saturation remained close to 0% for most periods and depths. These low variations may be due to fundamental limitations of the electromagnetic SM measurement technology used in this study, which cannot accurately quantify frozen water because of changes in dielectric permittivity during phase transition. Crucially, water residing in macropores, where PF typically occurs, is more susceptible to freezing because the influence of matrix potential on freezing-point depression is substantially reduced. Furthermore, even after correction of SM for temperature effects (Equation 2), a strong correlation between SM readings and temperature remained (see Figure S7 in Supporting Information S1), suggesting that the temperature correction was not effective. Further research

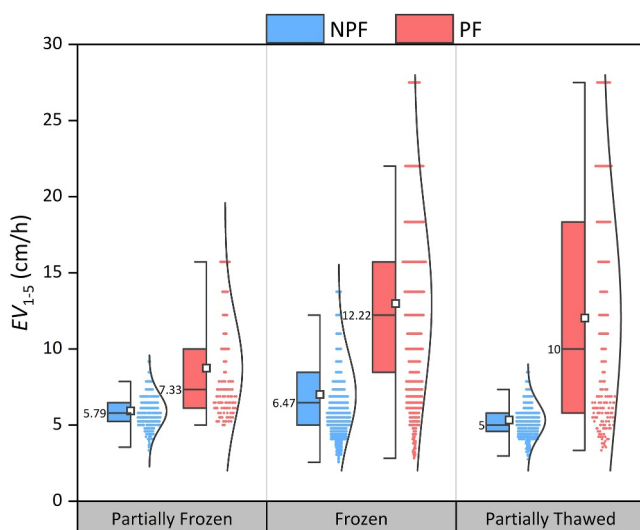


Figure 7. Velocity of energy transfer (EV_{1-5}) between the shallowest and deepest measurement depths obtained using Equation 10 for days with and without preferential flow during the three phases of the freezing periods.

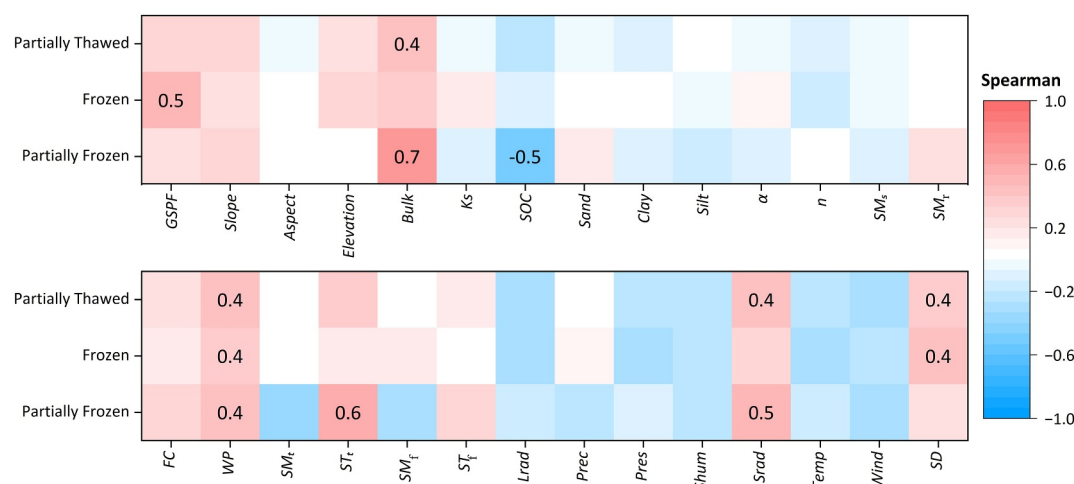


Figure 8. Spearman correlation coefficients between spatial factors (soil properties, topography, elevation, snowpack, meteorological conditions) and the frequency of preferential flow (PF) occurrence during the three phases of the freezing periods. The numbers in the figure represent the Spearman correlation coefficients that reached a significance level of 0.05. GSPF is the PF occurrence frequency during the non frozen period. Bulk, K_s , and soil organic carbon (SOC) represent bulk density, saturated hydraulic conductivity, and SOC, respectively. Soil moisture (SM), SM_s , α , and n are parameters of the soil water retention curve, while wilting point (WP) and field capacity (FC) represent WP and FC, respectively. SM_f , SM_t , ST_f , and ST_t represent SM (SM) and temperature (ST) at the beginning of the partially frozen (with subscript f) and the end of the partially thawed phases (with subscript t), respectively. Lrad, Prec, Pres, Shum, Srad, Temp, Wind represent the mean annual downward longwave radiation, precipitation, air pressure, specific humidity, downward shortwave radiation, air temperature, and wind speed at the measurement locations for the years 2014–2018. SD represents the mean annual snow depth.

should investigate the reasons for the ineffectiveness of the temperature correction in this study and explore the development of alternative correction methods that may perform more reliably (e.g., Bogena et al., 2017). Despite this, PF serves as a crucial pathway for energy transport, given the significantly higher specific heat capacity of water compared to soil. Our findings indicate that PF transfers energy more rapidly and efficiently to deeper soils (Kane et al., 2001; Watanabe & Kugisaki, 2017). The subsurface soil can receive twice as much energy on days when PF occurs (about 80% of RST at 5–15 cm, and about 47% of RST at 5–25 cm, with insignificant differences at 5–40 cm and 5–60 cm) compared to days without it (about 40% of RST at 5–15 cm, and about 20% of RST at 5–25 cm) (Figure 6). Additionally, PF results in energy propagation (about 12 cm/hr) at twice the speed of normal conductive heat transfer (i.e., heat transfer by atmospheric warming) (6 cm/hr) (Figure 7).

Our findings have revealed that frozen soils are not completely impermeable, highlighting the significant impact of PF on energy transfer (Koch et al., 2013; Mohammed et al., 2021). Specifically, the infiltration of meltwater into macropores and its subsequent refreezing induces frost heave, which expands existing pores and creates new PF pathways (Li et al., 2021). These expanded channels facilitate the rapid transport of surface water and its associated latent heat to deeper layers. This, in turn, triggers water movement to deeper soil through PF, constituting a positive feedback mechanism (Carey & Woo, 2013; Ebel et al., 2019; Mohammed et al., 2018; Zheng et al., 2019). It enables snowmelt to infiltrate deeper into the soil profile, accelerating soil thawing and deepening the active layer. In view of the fact that frozen soil is a significant reservoir of organic carbon, containing twice as much carbon as the atmospheric carbon pool (Jin & Ma, 2021; Koch et al., 2013; Zimov et al., 2006), and that climate-sensitive frozen soil zones are warming twice as fast as the global average (IPCC, 2023), frozen soil degradation leads to a rapid release of carbon into the atmosphere and aquatic systems (MacDougall et al., 2012). This released carbon further contributes to global warming and soil thawing, reinforcing the frozen soil-carbon feedback loop that is widely recognized (Ewing et al., 2015; Jin & Ma, 2021; Natali et al., 2021; Schuur et al., 2015).

4.2. Characterization of the Occurrence of PF in Seasonal Frozen Soil

Our study revealed different characteristics of PF occurrence in seasonal frozen soil across various phases, depths, and sites (Figures 3, 4 and 12 and Figure S7 in Supporting Information S1). Specifically, the lowest frequency of

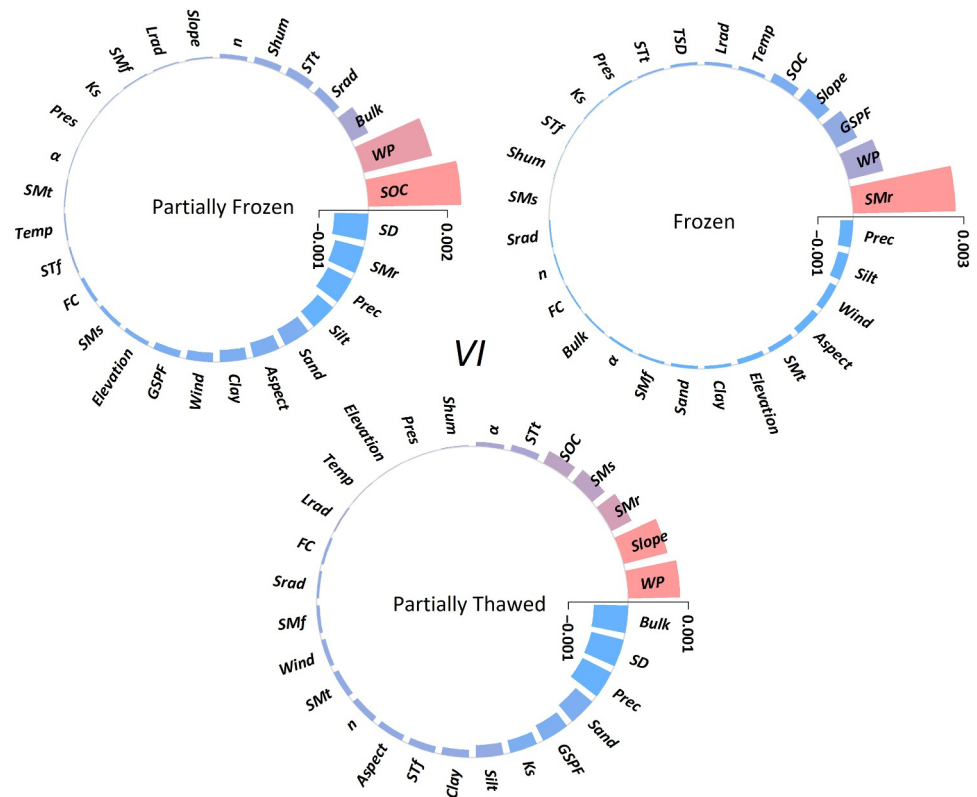


Figure 9. Importance of variables (variable importance (VI)) ranked in descending order for the frequency of preferential flow (PF) occurrence. Higher values correspond to taller bars, with colors closer to pink indicating a greater impact on PF. Due to missing soil properties data for some stations, only 25 stations were used for VI ranking. The abbreviations have the same meaning as in Figure 8.

PF was observed during the partially frozen phase, followed by the partially thawed phase, while the fully frozen phase exhibited the highest frequency. Notably, the partially thawed phase demonstrated a higher PF frequency compared to the partially frozen phase. This phenomenon can be attributed to the fact that, during the partially thawed phase, the combination of residual snow cover at the land surface and rising air temperatures triggers rapid snowmelt (He et al., 2023; Mohammed et al., 2021). This process not only delivers abundant liquid water to the surface but also contributes substantial thermal energy. It is precisely this spatiotemporal coupling of increased water availability and energy input that creates the necessary conditions to drive water migration and establish PF pathways.

Despite these differences, the spatial distribution of PF remained consistent across various sites during the freezing period. This suggests that PF is influenced by similar spatial factors, such as soil properties, throughout different freezing phases. Moreover, differences exist in the most critical spatial factors influencing the occurrence of PF during freezing periods (Figure 9).

Specifically, SOC is influential during the partially frozen phase, while SM_r is significant during the frozen phase, and the WP is crucial during the partially thawed phase (Figure 9). Previous work in this region showed that the explanatory variables for the frequency of PF occurrence during the non-freezing phase were K_s, SM_r, and SOC (Kang et al., 2023).

The factors controlling the occurrence of PF, both during freezing and non-freezing periods, are related to pore characteristics. As a first approximation, the pore size distribution can be derived from the SM retention curve (Fouli et al., 2013; Sun et al., 2024). This relationship stems from the connection between pore size and soil water retention: larger pores drain more readily under drier conditions, whereas smaller pores retain water longer

Table 2
The Training (errT) and Validation Error (errV) of the Different Decision Trees During the Three Phases of the Freezing Period

Phases	errT	errV
Partially Frozen	0.14	0.18
Frozen	0.13	0.15
Partially Thawed	0.14	0.13

Note. The error represents the misclassification rate of decision trees in distinguishing between preferential and non-PF events.

Table 3

Variable Importance of Temporal Factors Influencing the Occurrence of Preferential Flow During Freezing Periods Using Classification and Regression Trees

Phases	STI _{max}	STI _{min}	AT	Srad	Lrad	SDC
Partially Frozen	36.51	31.51	23.83	31.92	21.63	38.61
Frozen	105.66	73.36	88.07	85.20	70.33	136.17
Partially Thawed	87.37	39.39	48.53	32.38	43.16	62.52

(Amankwah et al., 2021). Specifically, the parameters WP and SM_r of the SM retention curve indicate the water content held in pores of different sizes under specific drying conditions. Since SM_r corresponds to a drier state than WP, the effective pore diameter associated with WP is larger. The factors influencing PF across freezing phases are therefore linked to the dominant sizes of pores that remain available for liquid water flow. In the partially frozen phase, most soil water is unfrozen, and macropores act as the primary pathways for PF. This is consistent with findings that SOC, which promotes macropore formation and stability, is a key control on PF during this phase (Dekker & Ritsema, 1996; Guo & Lin, 2018). As temperatures drop further,

water in macropores (distant from soil particles) freezes first, blocking these larger pathways. Consequently, during the fully frozen phase, any remaining liquid flow is confined to a network of much smaller, unfrozen pores. Within this restricted network, PF, if it occurs, would likely utilize the largest remaining unfrozen pathways, whose effective conductive size is nonetheless greatly reduced by ice. Therefore, SM_r—which represents water held tightly in the finest pores—serves as an indicator of the pore space most resistant to freezing and thus pertinent to flow under fully frozen conditions (Figure 9). In contrast, during the partially thawed phase, ice melts first from the surfaces of soil particles and smaller pores, progressively reopening flow paths of increasing size. Water movement through these newly accessible, initially small but expanding pores becomes the dominant PF mechanism. Hence, WP—associated with water held in larger, drainable pores—emerges as the main factor controlling PF during thaw as these pathways become ice-free and conductive.

In addition to soil properties, the occurrence of PF is influenced by various hydrothermal factors (Demand, Selker, & Weiler, 2019; Scherler et al., 2010; Watanabe & Kugisaki, 2017). We have found that the SDC is the primary temporal factor influencing the occurrence of PF in frozen soil. In a classification tree determining whether PF occurs, the SDC controls all nodes across all phases of the frozen period, as well as most nodes during partially frozen and partially thawed phases. This implies that snowmelt serves as the primary moisture source for PF during freezing periods. In addition, soil temperature at the shallowest measurement depth also influences PF occurrence during partially thawed and partially frozen phases, implying that water from melted ice in the upper soil also contributes to PF.

Previous studies have highlighted the significant impact of initial SM on the occurrence of PF in seasonal frozen soil (Watanabe & Kugisaki, 2017; Watanabe et al., 2012). However, due to limitations in SM observation methods (Bogena et al., 2017; He & Dyck, 2013), we were unable to analyze this effect directly. Nonetheless, we attempted to assess the effect of pre-freezing SM (SM_p) on PF but did not find a significant relationship (Figure 8). This lack of significance could be attributed to lower rates of water supply in the study area. Precipitation in the study area ranges from 200 to 700 mm, while snowfall accounts for only about 20% of the total rainfall (Geng et al., 2014; Wang et al., 2023).

It is worth noting that the frequency of PF occurrence at two of the three shrub sites (S1 and S2) was significantly lower than at site S3 (Figure 4). This trend was opposite to that observed during the non-frozen periods (Kang et al., 2023). Upon analyzing the SM and snow depths at the beginning of the freezing periods at these three sites, we found that, although the cumulative multi-year snow depths (about 100 mm) at the three sites were similar, the SM at the beginning of the freezing periods at S1 and S2 was much higher than that at S3 (SM of S1: 30.17 vol.%; S2: 29.97 vol.%; S3: 8.61 vol.%). Consequently, water in the freezing periods froze and clogged the pore space, resulting in a lower percentage of PF at S1 and S2 (Mohammed et al., 2018; Watanabe et al., 2012).

Figure 12 summarizes the characteristics of PF in the study area across different phases of the freezing period and the non-frozen phase. The impact of PF on water and energy transfer within the soil system varies across different periods (Kang et al., 2023). During non-frozen periods, PF predominantly influences water movement due to the absence of phase changes in water and significant water recharge (Figure 12) (Kang et al., 2022, 2023). Conversely, during freezing periods, the limited surface water supply diminishes the impact of PF on water movement, yet the higher specific heat capacity of water underscores its influence on energy transfer, which cannot be overlooked (Figures 6, 7 and 12). Moreover, while certain similarities exist, there are also differences in the influences of PF within the study area (Figure 12). Moisture input characteristics, such as SDC during the freezing period and rainfall intensity and amount during the non-frozen period, consistently influence PF

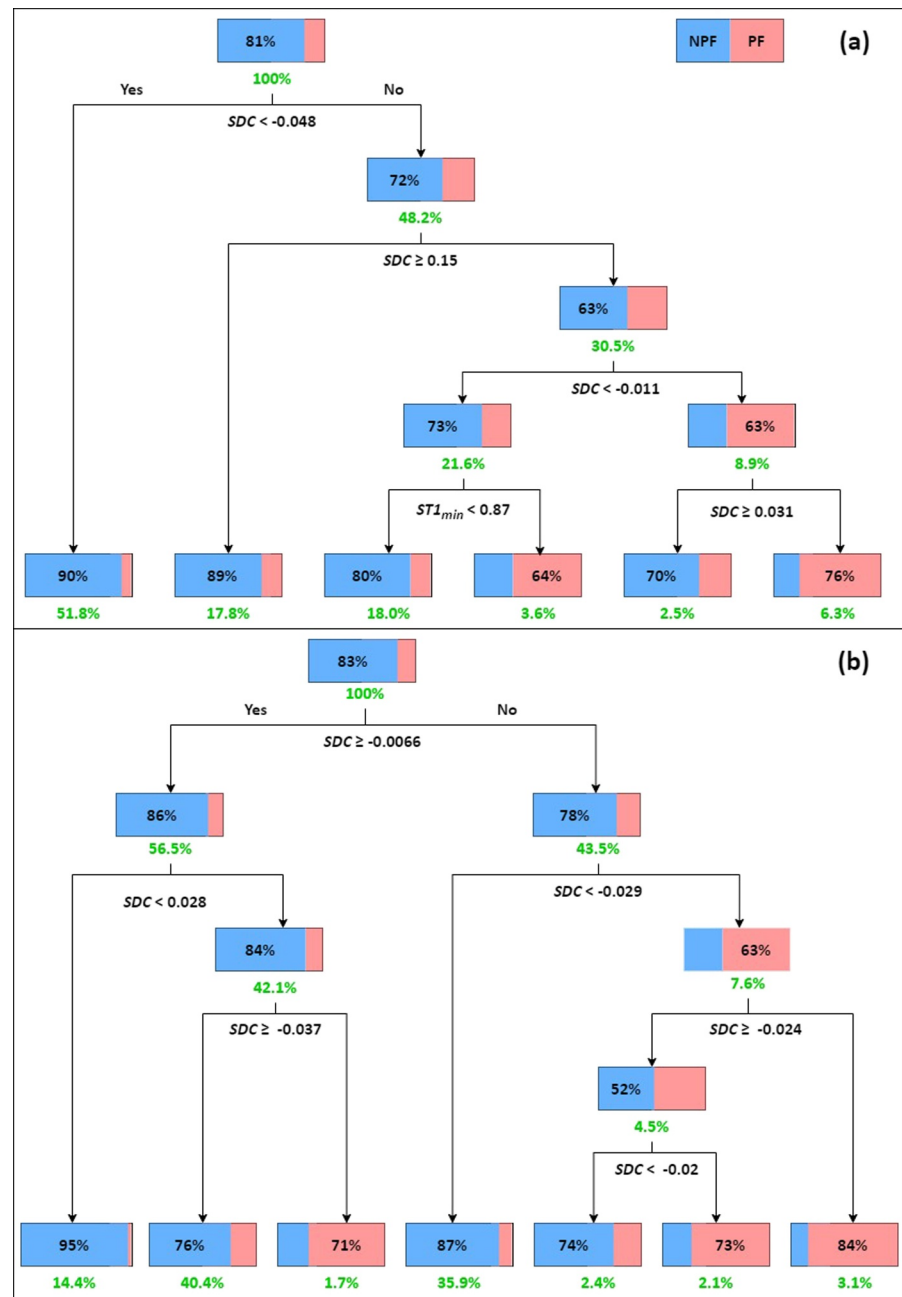


Figure 10. Classification tree of preferential flow (PF) occurrence for all stations generated by classification and regression trees for the partially frozen phase (a) and frozen phase (b). The red and blue columns are the nodes of the tree and represent without PF events and PF events, respectively. The size of the different colored columns and the number in the column indicate the proportion of the corresponding type of events in that node. The green number below the node indicates the proportion of observations for that node to the total number of events. The values of the explanatory variables for each node are standardized. SDC and $ST1_{min}$ represent snow depth changes rate and minimum value of soil temperature in the shallowest measurement depth, respectively.

throughout the freeze-thaw cycle. However, during the freezing period, the influence of macropores and associated soil properties on PF diminishes, with SOC found to affect PF occurrence solely during the freezing phase (Figures 9 and 12).

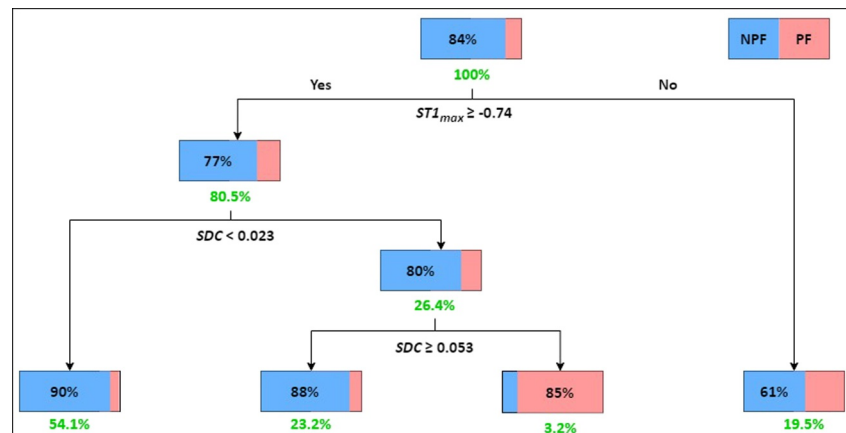


Figure 11. Classification tree of preferential flow occurrence for all stations generated by classification and regression trees in the partially thawed phase. The meaning of the elements in the figure is the same as in Figure 10. $ST1_{max}$ represents the maximum value of soil temperature at the shallowest measurement depth.

4.3. Limitations and Future Considerations

We identified potential PF events in seasonally frozen soil at a high temporal resolution (day-scale or event-scale, i.e., a single snowmelt or frozen soil thaw event) by analyzing the sequence of peak soil temperatures at different depths. Direct detection of PF via SM anomalies was not feasible, as the sensor readings were subject to significant temperature-induced fluctuations even after temperature correction (Bogena et al., 2017; He & Dyck, 2013; Saito et al., 2013). While this single-method approach lacks independent verification, the inferred PF events exhibited impacts on thermal signal propagation consistent with conceptual models of rapid water movement (Figures 5–7), aligning with previous studies (Demand, Selker, & Weiler, 2019; Hu et al., 2023; Larsbo et al., 2019; Mohammed et al., 2018). The RST and EV_{1-5} metrics were used to quantify the relative intensity of these thermal impacts (Figures 6 and 7). However, their interpretation is constrained by the absence of precise, depth-resolved volumetric soil water content data, which precluded the accurate calculation of soil heat capacity and latent heat fluxes during phase changes. Consequently, RST (and EV_{1-5}) serve as comparative

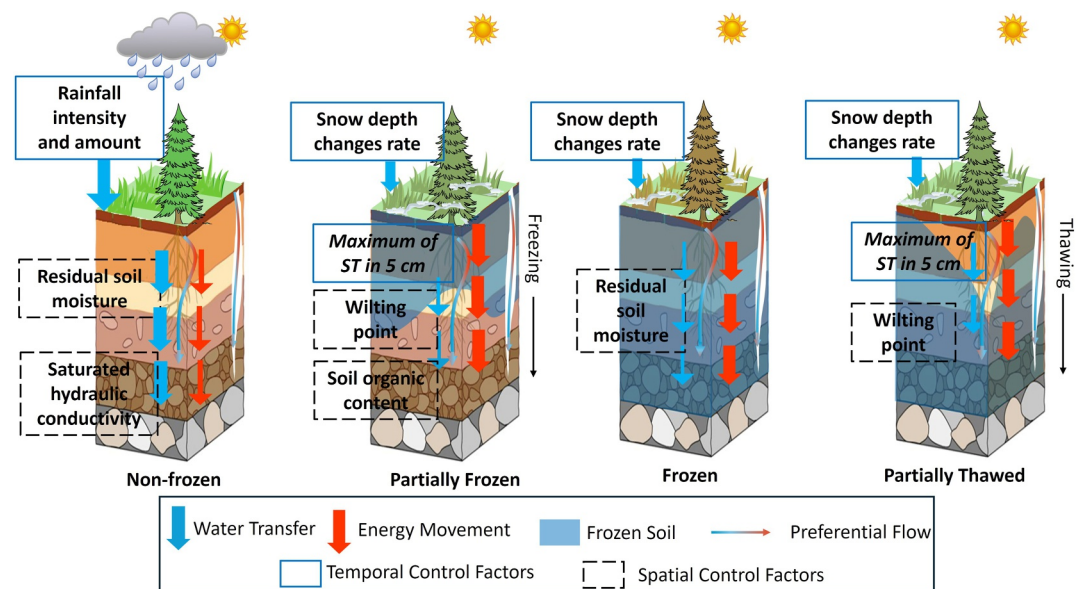


Figure 12. The effect of preferential flow (PF) on soil moisture transport and energy transfer during freeze-thaw cycles, and the factors controlling the distribution of PF (highlighted by the black dashed box in the figure) and determining its occurrence (highlighted by the blue solid box in the figure) at each period.

indices of thermal coupling strength, not as complete energy balance ratios. The estimated energy transfer likely represents a conservative lower bound, as latent heat effects associated with enhanced water transport remain unaccounted for.

Identifying PF from soil temperature relies on noticeable daily fluctuations in soil temperature at various depths (Figure 2). However, this method may encounter limitations due to several reasons:

1. As soil depth increases, soil temperature becomes less influenced by AT. Consequently, soil temperatures in greater depths, such as at 60 cm depth in our study, may exhibit minimal fluctuations that make it impossible to determine the moment when the temperature peak occurs (Popiel et al., 2001; Shukla et al., 2019). This makes it difficult to detect PF using the methods used in this study. However, during the freezing period, PF can facilitate the transfer of a significant amount of energy (Figures 6 and 7). Consequently, the occurrence of PF may induce abnormal changes in soil temperature. Thus, analyzing anomalous changes in deep soil temperature remains a viable approach to identifying PF in frozen soil.
2. During partially frozen and thawed phases, particularly in areas with high SM, there may be a “zero curtain” phenomenon where temperatures approach 0°C. During this time, heat transfer in the soil due to latent heat is more significant than that caused by heat conduction or water convection (Hinkel et al., 2001; Hu et al., 2023; Yu et al., 2018). Consequently, soil temperatures remain near 0°C for extended periods, making it challenging to identify PF based on temperature fluctuations. Therefore, there may be errors in identifying the frequency of PF occurrence during the partially frozen and partially thawed phases in this study (Figures 3 and 4).
3. Forest canopies exert a significant influence on radiation, resulting in a notable reduction in the variability of soil and AT (Beltrami & Kellman, 2003; Karlsson, 2000; Kubin & Kemppainen, 1991). This thermal damping effect confines measurable daily soil temperature fluctuations primarily to shallow depths (e.g., 5 cm), while deeper layers exhibit minimal thermal variability (<0.1°C amplitude). Consequently, the minimal soil temperature amplitude impedes accurate determination of thermal peak timing at depths >5 cm, which is a prerequisite for PF identification using thermal response methods. At the forested sites of this study (F1–F3), these physical constraints likely resulted in substantial underestimation of PF occurrence (Figure 4).

Despite these limitations, it was possible to identify PF during most of the freezing periods based on soil temperature variations at different depths. This method allows for long-term field observations of PF in frozen soil. In contrast, most previous methods for observing PF during the freezing periods involved indoor experiments (Watanabe et al., 2012; Watanabe & Kugisaki, 2017) or cannot be continuously observed (Demand, Selker, & Weiler, 2019; Espeby, 1990; Stähli et al., 2004). Additionally, SM and temperature sensors such as 5TE and Thermo-TDR (Topp & Davis, 1985) can simultaneously observe soil temperature and SM. By leveraging the complementary strengths of these dual measurements, we can characterize PF throughout the entire freeze-thaw cycle: utilizing temperature anomalies as a robust indicator during the frozen phases (when moisture sensors are less reliable) and relying on SM dynamics during the thawed periods (Demand, Blume, & Weiler, 2019; Kang et al., 2023).

5. Conclusions

PF plays a critical role in shaping water movement and energy transfer dynamics within frozen soil. In this study, we employed soil temperature data at various depths to identify daily/event-scale PF and investigate their impacts on frozen soil hydrothermal characteristics and underlying mechanisms. Here are the key findings of our study:

- Compared to non-PF periods, PF events are associated with significantly stronger and faster propagation of thermal signals from the surface to deeper soil.
- Utilizing the random forest method, we observed variations in the factors controlling PF occurrence across different freezing phases, with soil organic content influencing the partially frozen phase, residual SM affecting the frozen phase, and WP playing a role in the partially thawed phase.
- Employing classification and regression trees, we established the occurrence pattern of PF across different freezing phases. We identified the snow depth changes rate as the primary determinant of PF occurrence, followed by surface soil heat characteristics (minimum and maximum and value of soil temperature).
- Throughout the freeze-thaw cycle, the effects of PF on water movement and energy transfer, along with the mechanisms of its occurrence, exhibited variability across different phases.

Our study underscores the feasibility of identifying PF in frozen soils through soil temperature monitoring at varying depths. Additionally, our findings emphasize the significant influence of PF on soil hydrothermal characteristics in alpine mountainous regions and offer novel insights into the mechanisms driving PF occurrence.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Matlab (R2022a, The MathWorks) was used to identify infiltration events and to process the data, and the R (v4.1.3; R Core Team, 2022) packages “rpart”, “part.plot” and “VSURF” were used to perform classification and regression trees and random forest analysis. Meteorological and snow data are available for download at the National Tibetan Plateau Data Center (<https://data.tpdc.ac.cn/en/>). The main scripts (identifying PF events, classification and regression trees, and random forest), the identified PF events and their characteristics, and the key results obtained in this study can be found from Kang (2025). <https://doi.org/10.6084/m9.figshare.26500222.v2>.

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Erratum

The originally published version of this article omitted contributions for coauthor Chansheng He, who contributed to Funding acquisition, Supervision, and Writing – review & editing. The error has been corrected, and this may be considered the authoritative version of record.