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Frozen Soil Hydrological Processes and Their Effects: A Review and Synthesis

Ying Zhao[1,2], Ce Zheng[3], Alexander Gelfan[4,5], Kunio Watanabe[6], Haojie Liu[7], Stephanie Wright[8], Xiaolong Wu[8,9], William Quinton[10], Yi Wang[1], Shuhua Yi[11], Yongyong Zhang[12], Yujie Shi[13,14], and Wentao Jiao[14]

[1]School of Hydraulic and Civil Engineering, Ludong University, Yantai, China, [2]Global Institute for Water Security, University of Saskatchewan, Saskatoon, SK, Canada, [3]School of Water and Environment, Chang'an University, Xi'an, China, [4]Department of Hydrology, Faculty of Geography, Moscow State University, Moscow, Russia, [5]Water Problems Institute, Russian Academy of Sciences, Moscow, Russia, [6]Graduate School of Bioresources, Mie University, Tsu, Japan, [7]Faculty of Agricultural and Environmental Sciences, University of Rostock, Rostock, Germany, [8]Department of Civil Engineering, Queen's University, Kingston, ON, Canada, [9]Morwick G360 Institute for Groundwater Research, University of Guelph, Guelph, ON, Canada, [10]Wilfrid Laurier University, Waterloo, ON, Canada, [11]State Key Laboratory of Herbage Improvement and Grassland Agro-Ecosystems, Lanzhou University, Lanzhou, China, [12]National Field Science Research Station of Farmland Ecosystem in Linze, Key Laboratory of Ecological Safety and Sustainable Development in Arid Lands, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China, [13]Key Laboratory of Vegetation, Ecology of the Ministry of Education, Institute of Grassland Science, Jilin Songnen Grassland Ecosystem National Observation and Research Station, Northeast Normal University, Changchun, China, [14]Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China

Key Points:

- Synthesizes frozen-soil hydrology across scales, unifying freeze-thaw dynamics, infiltration regimes, and groundwater-permafrost links
- Thaw reorganizes flow paths toward deeper groundwater, shifting runoff seasonality, water quality, ecosystems, and greenhouse-gas fluxes
- Outlines a tiered modeling path and priority observations to parameterize ice-impeded hydraulics, thresholds, and abrupt-thaw processes

Correspondence to:

Y. Zhao and W. Jiao,
yzhaosoils@gmail.com;
wtjiao@rcees.ac.cn

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Author Contributions:

Conceptualization: Ying Zhao, Ce Zheng, Alexander Gelfan, Kunio Watanabe, Haojie Liu, Wentao Jiao
Data curation: Ce Zheng
Funding acquisition: Ying Zhao
Investigation: Ying Zhao, Stephanie Wright, Yi Wang, Shuhua Yi, Yujie Shi
Methodology: Ying Zhao, Alexander Gelfan, Kunio Watanabe, Haojie Liu, Shuhua Yi
Project administration: Ying Zhao
Resources: Ying Zhao, Ce Zheng, Haojie Liu, Xiaolong Wu, Yi Wang, Shuhua Yi, Yongyong Zhang, Yujie Shi
Software: Ce Zheng, Xiaolong Wu
Supervision: Ying Zhao
Validation: Kunio Watanabe, Haojie Liu
Visualization: Ying Zhao, Ce Zheng

Abstract Frozen soils, including seasonally frozen ground and permafrost, are rapidly changing under a warming climate, with cascading effects on water, energy, and carbon cycles. We synthesize recent advances in the physics, observation, and modeling of frozen-soil hydrology, emphasizing freeze–thaw dynamics, infiltration regimes and preferential flow, groundwater–permafrost interactions (including talik development and advective heat), and resulting shifts in streamflow seasonality. Progress in in situ sensing, geophysics, and remote sensing now resolves unfrozen water, freezing fronts, and active-layer dynamics across scales, while land-surface and tracer-aided hydrological models increasingly represent phase change, macropore bypass, and vapor transport. Thaw-induced activation of subsurface pathways alters recharge and baseflow, influences vegetation and biogeochemistry, and modulates greenhouse-gas emissions. Key uncertainties persist in scaling micro-scale processes, parameterizing ice-impeded hydraulics, and representing abrupt thaw and wetland dynamics. We outline a tiered modeling framework, priority observations, and integration of vegetation–hydrology–carbon processes to improve projections of cold-region water resources and climate feedbacks.

Plain Language Summary Frozen ground acts like a seasonal or long-term underground dam that controls how water moves and how carbon is stored. As the climate warms, these frozen layers thaw. Water then takes new routes underground, changing when rivers rise, how wetlands behave, and influencing how much greenhouse gas escapes to the atmosphere. Scientists now use improved soil sensors, drones, satellites, and computer models to track these changes from the pore scale to whole regions. The big challenges are connecting fine-scale ice–water processes to landscape behavior and capturing sudden thaw events that can rapidly reshape terrain. Better monitoring and models, especially those assessments that combine plants, water, and carbon, will help communities manage water, protect infrastructure, and plan for climate change in cold places.

1. Introduction

Frozen soil, including seasonally frozen ground (SFG) and permafrost (perennially frozen ground), covers roughly 20% of the Earth's land surface (G. Hu et al., 2023), including 55%–60% of the Northern Hemisphere (T. Zhang et al., 1999), 75% of China (T. Zhang et al., 1999) and 90% of Russia (Kudryavtsev, 1977) (Figure 1). The presence or absence of ice in soil pores directly affects soil thermal and hydraulic properties, water and energy balances, and even local climates (Poutou et al., 2004) (Figure 2). For example, ice-filled pores and lenses can block infiltration and evaporation, triggering floods and increasing infrastructure damage (A. N. Gelfan, 2010), yet these processes may also increase topsoil moisture, benefiting crops and ecosystems. Understanding freeze-thaw (FT) dynamics and its effect on hydrological processes is also important in high-latitude and

Writing – original draft: Ying Zhao, Ce Zheng, Alexander Gelfan, Stephanie Wright, Xiaolong Wu, Yujie Shi
Writing – review & editing: Ying Zhao, Kunio Watanabe, Haojie Liu, William Quinton, Yi Wang, Yongyong Zhang, Wentao Jiao

high-altitude environments where the active layer above permafrost seasonally freezes and thaws. Additionally, FT processes are becoming increasingly important as permafrost regions transition to SFG under climate change. Understanding frozen soil hydrology and its mechanical, biogeochemical, and ecohydrological processes is essential, but complex FT dynamics, soil heterogeneity, ice formation, and surface and subsurface water interactions complicate monitoring and modeling efforts.

Over recent decades, climate warming has reduced SFG and permafrost extent in the Northern Hemisphere by roughly one-tenth (J. Li et al., 2021; Obu et al., 2019), with additional implications for hydrological, geotechnical, and biogeochemical processes. Rapid snowmelt infiltration into thawing soils leaches nutrients, degrading groundwater and surface-water quality and intensifying erosion and sediment loads (Hayashi, 2013). Warmer groundwater and soils driven by rapid increases in air temperature threaten water quality, groundwater-dependent ecosystems, and ground stability (Figura et al., 2011; Kurylyk et al., 2014). Similarly, permafrost degradation reduces soil strength, increases subsidence risks, and modifies carbon cycles (Chen et al., 2021; S. L. Smith et al., 2022). With permafrost regions storing over 50% of global soil organic carbon (~1,700 Gt) (Miner et al., 2022), thawing permafrost can release carbon dioxide (CO_2), methane (CH_4), and dissolved organic carbon (DOC), thereby accelerating positive climate feedbacks (Harden et al., 2012; Hjort et al., 2018; Hugelius et al., 2020; E. A. Schuur et al., 2015). As a result, frozen soil hydrology is increasingly viewed as a critical component of the Earth system, with its responses to warming potentially acting as a tipping element in the global climate (Natali et al., 2021).

Research on frozen soil hydrology is inherently interdisciplinary, linking soil physics, hydrology, geocryology, climatology, and ecology. Despite the importance of frozen soil on global-scale processes (e.g., carbon-climate feedbacks), its hydrological processes have long been under-represented in global studies. As such, there is an urgent need to describe key frozen soil hydrological processes, controlling factors, and associated research challenges and opportunities. In response, a structured bibliometric scan was conducted and complemented by expert synthesis (Figure 3). Three thematic clusters emerged: (a) key parameters and modeling; (b) hydrological processes; and (c) climate change. These clusters were used to structure Sections 2–6, which review the advances in the theory, quantification, and applications of frozen soil hydrological processes, and identify recommendations for future research directions.

This review advances frozen-soil hydrology by (a) integrating SFG and permafrost into a single framework that unifies infiltration regimes, macropore flow, and advective heat transfer; (b) providing a practical parameterization guide that aligns water retention curves with thermal and hydraulic conductivities and ice-impedance, including dual-domain options; (c) setting out a tiered modeling roadmap, from process-level to intermediate-complexity to land-surface/Earth-system models, with explicit data and evaluation targets; and (d) making explicit links between thaw-driven groundwater connectivity, water quality, carbon–energy feedbacks, and infrastructure risks.

2. Processes of Water Flow and Heat Transfer in Frozen Soil

Frozen soil physics addresses how water and heat interact, move, and accumulate in frozen ground under the influence of climate, soil properties, and vegetation. Key processes include soil FT cycles, infiltration, runoff generation, evapotranspiration, moisture redistribution via cryosuction (i.e., the upward suction of water toward freezing fronts), and the interactions with groundwater. These soil FT cycles profoundly affect ecological systems, nutrient cycles, and infrastructure integrity (Figure 2). While individual processes are relatively well understood, considerable uncertainty remains regarding their interactions and feedback mechanisms.

2.1. General Issues of Frozen Soil Physics and Hydrology

Frozen soil consists of solid particles, ice, liquid water, and air (Figure 4). The coexistence of ice and liquid water markedly alters soil hydrothermal properties, mechanical strength, and heat and moisture exchanges with the atmosphere (Farouki, 1986; Hansson et al., 2004; Lawrence & Slater, 2008; Lundin, 1990; Nitzbon et al., 2020). Ice, with a thermal conductivity four times that of water, strongly influences the soil thermal regime, whereas pore ice blocking water pathways greatly reduces hydraulic conductivity. The presence of ice also increases soil volume (frost heave) and cementation, thus affecting mechanical stability.

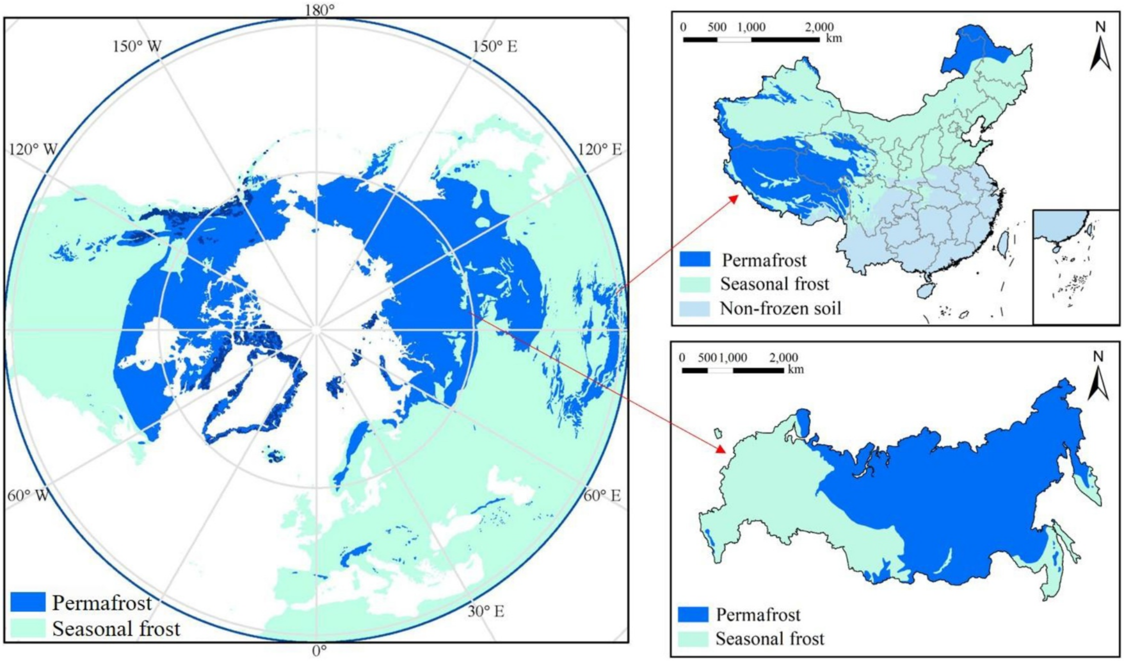

Figure 1. Frozen soil distribution of the Northern Hemisphere, China, and Russia. The map illustrates the extent of permafrost (continuous, discontinuous, sporadic) and seasonally frozen ground. *Data source: National Cryosphere Desert Data Center* (http://www.ncdc.ac.cn) *and synthesis of recent permafrost maps.*

Water in frozen soils moves through hydraulic gradients and vapor diffusion. As freezing draws liquid to form ice lenses, thawing releases stored water, sharply raising soil moisture. Appropriate estimations of ice content are therefore critical to predicting frozen soil behavior (G. Hu et al., 2020; T. Hu et al., 2020). Methods include energy-balance approaches using latent heat (Jansson, 2012) and freezing-point depression analysis via the Clausius–Clapeyron equation (Hansson et al., 2004), though the latter may not be accurate under non-equilibrium conditions (Kurylyk & Watanabe, 2013). Frozen soils also exhibit very high apparent heat capacity, releasing or absorbing ∼80 times more energy during phase change than water during normal heating, which buffers soil temperature and redistributes energy (Lawrence & Slater, 2008; Poutou et al., 2004; Viterbo et al., 1999). Recent studies further highlight the importance of non-conductive heat transfer. For example, the advective heat transport by liquid water and vapor may dominate under conditions of preferential flow and high permeability, especially during snowmelt infiltration or rain-on-snow events (Kurylyk et al., 2014; Yu et al., 2018). These findings demonstrate that conductive-only representations systematically underestimate active-layer thaw depth, zero-curtain persistence, and rates of permafrost thaw (Devoie et al., 2021).

Two principal theories govern water and heat transport in frozen soils. First, the soil water potential theory, dominant since the 1960s, posits that differences in soil water potential drives water movement, using the Clausius-Clapeyron equation to link ice content with sub-freezing temperature or pressure (Kurylyk & Watanabe, 2013). Second, the hydrodynamics theory identifies three drivers of water transport: water movement, heat transfer, and phase changes (H. Ran et al., 2019). Despite their conceptual differences, both theories provide essential frameworks for modeling thermal-hydraulic interactions in frozen soils. Nonetheless, no universally accepted theory fully captures FT processes, highlighting the need for continued theoretical refinement and validation (Endrizzi et al., 2014). In particular, recent intercomparisons of thermo-hydrologic models show large discrepancies in predicting soil ice content and thaw depth, driven by differences in freezing-curve parameterizations and treatment of unfrozen water (Bui et al., 2020; Grenier et al., 2018). These discrepancies underscore the critical role of parameterization in reducing uncertainty. Hydrodynamic models, for instance, do not explicitly address frost heave which is linked to heat and water movement in saturated soils during freezing (Guymon et al., 1980; K. O'Neill & Miller, 1985), but have been proven to be effective for simulating active-layer hydrology (Cao et al., 2021).

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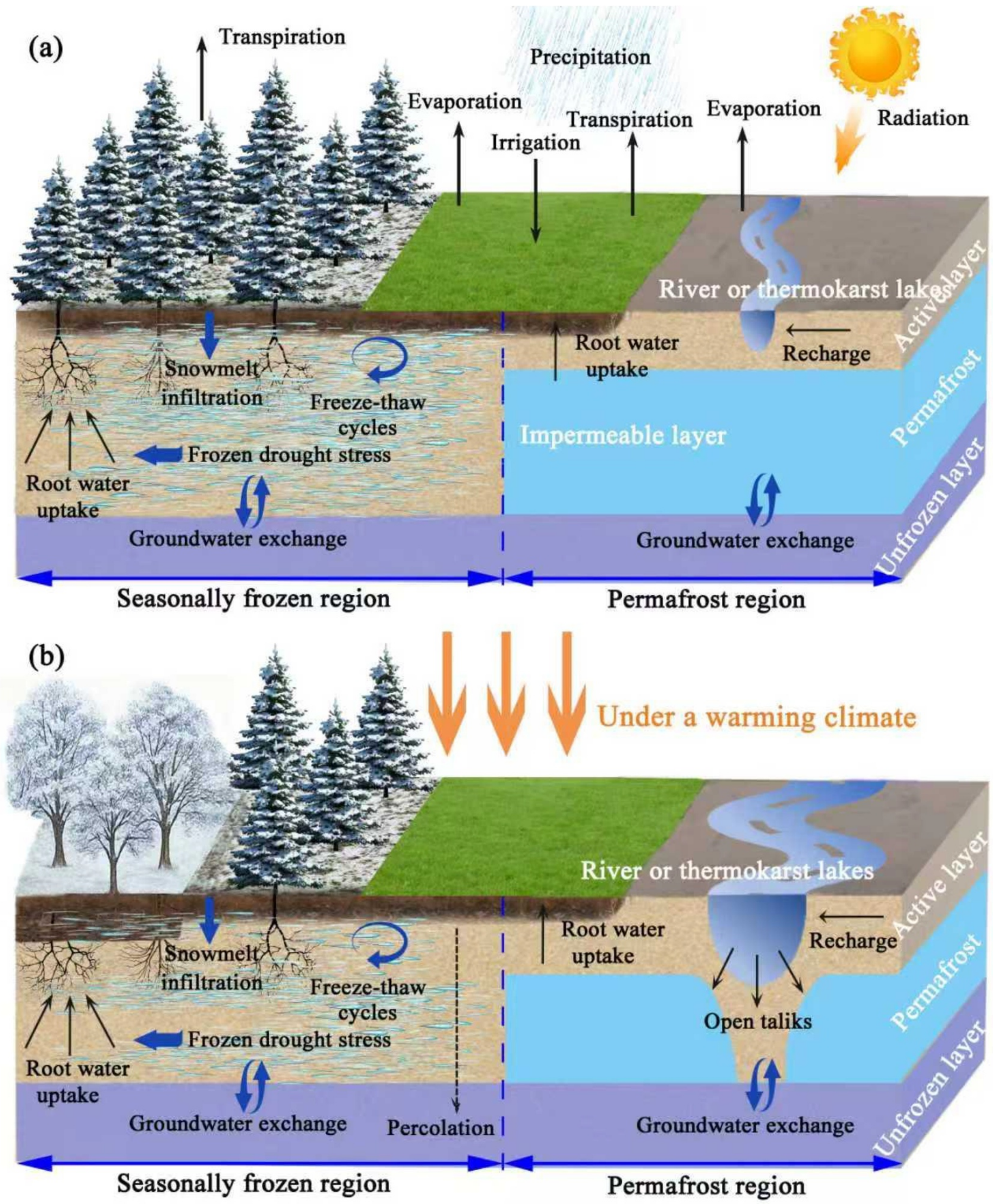

Figure 2. The conceptual model of hydrological processes in frozen soil regions under (a) current and (b) future conditions. Schematic of permafrost-dominated (left) versus seasonally frozen ground (SFG) watersheds (right). Permafrost impedes infiltration, concentrating surface runoff and shallow flow; SFG thaws annually, enabling deep recharge, higher year-round baseflow, and greater soil-moisture storage despite a shallow winter frozen layer.

2.2. Water-Cycle Mechanisms in Frozen Soils

Soil FT processes significantly impact soil moisture regimes, thermal properties, evaporation, infiltration, albedo, texture, and structure (Frampton & Destouni, 2015; Nitzbon et al., 2020), thereby influencing water and energy exchanges with the atmosphere (Viterbo et al., 1999). Interactions between groundwater and surface water in frozen soils can shift recharge and discharge zones, promote thermokarst formation, and increase river baseflow as the permafrost degrades (Geyman et al., 2024; J. Li et al., 2021; J. Xie et al., 2024). Together, these studies indicate that once ice content exceeds a threshold, infiltration dramatically decreases and water movement shifts to increased runoff.

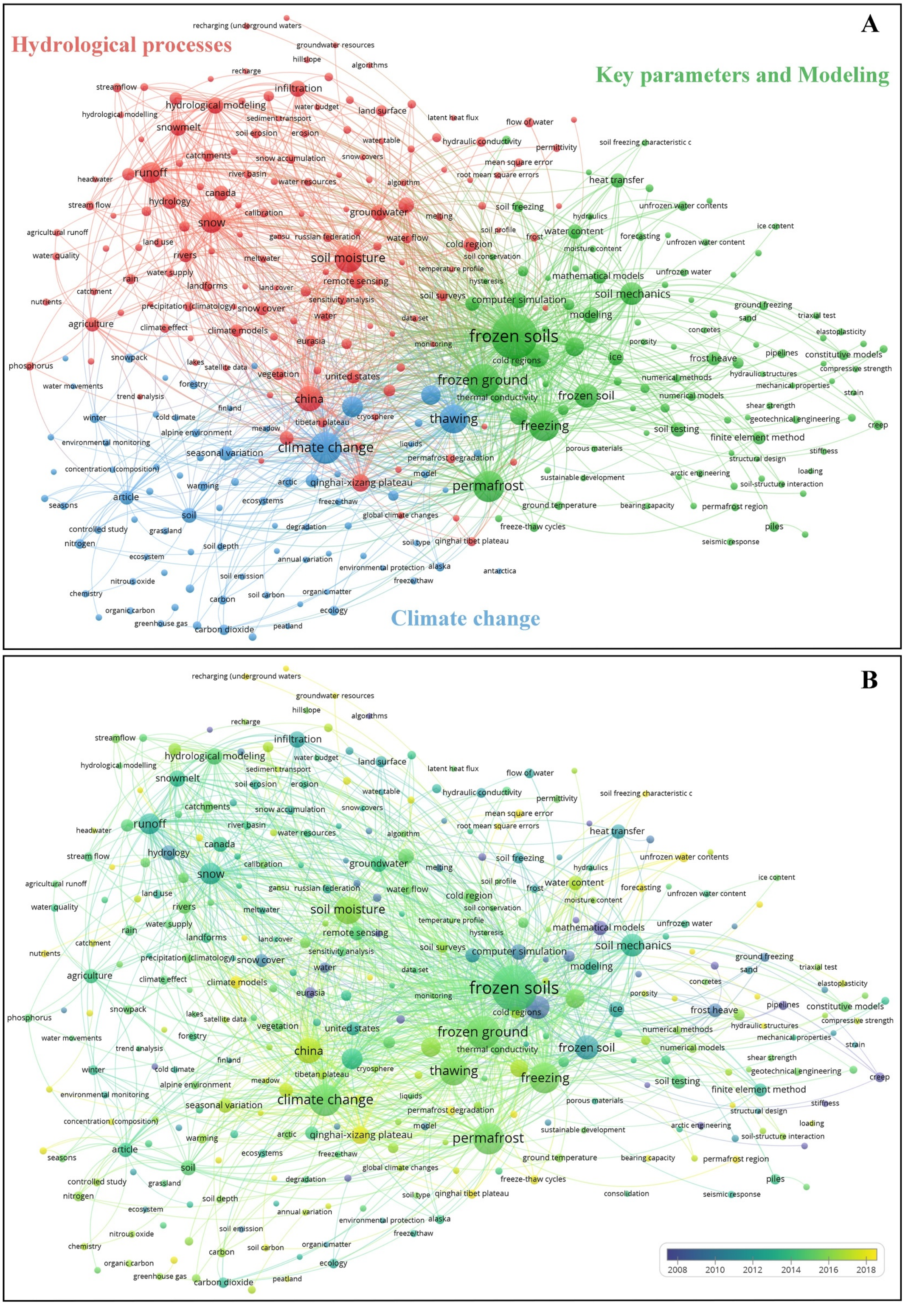
A
Hydrological processes
Key parameters and Modeling
Climate change
B
2008
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Figure 3.

Infiltration into frozen soils is governed by a continuum of regimes from unrestricted percolation (gravity-driven) to limited or restricted infiltration where capillary forces and ice blockage impede water entry. Soil texture, antecedent moisture content, frost depth, temperature gradients and midwinter refreeze events all modulate hydraulic conductivity and gas diffusion (Appels et al., 2018; Granger et al., 1984; Gray et al., 2001; Johnson & Lundin, 1991; Kane & Stein, 1983). Threshold behaviors have been observed experimentally, wherein slight changes in FT status or soil texture cause abrupt shifts between infiltration regimes (Sanchez-Rodriguez et al., 2025; Stuurop et al., 2022). High ice content layers formed by antecedent wet conditions significantly reduce infiltration capacity, leading to increased spring flooding and enhanced surface runoff and erosion, while drier and/or coarse-textured soils may still maintain preferential macropore flow (Mohammed et al., 2018; Walvoord & Kurylyk, 2016). Recent laboratory experiments confirm that soil texture and antecedent water content strongly control the formation of impermeable ice lenses and thus influences infiltration capacity during snowmelt (R. Jiang et al., 2024).

Thawing of SFG increases vertical percolation and lateral redistribution of water, sometimes forming perched aquifers that modulate snowmelt-driven recharge and summer rainfall infiltration (Bayard et al., 2005; Iwata et al., 2008). Snowmelt infiltration often penetrates deeper than rainfall infiltration, depending on the snow water equivalent and melt rate (H. He, Dyck, Si, et al., 2015; H. He, Dyck, Wang, et al., 2015). Preferential flow through soil macropores and cracks may lead to uneven infiltration and rapid routing of snowmelt in partially frozen soils, emphasizing the importance of representing such processes in hydrological models (Watanabe & Kugisaki, 2017). Frozen soil properties also differ by texture, increasing macroporosity and hydraulic conductivity in clay soils but reducing these processes in sandy soils (Starkloff et al., 2017). Advancing such macropore–matrix interaction schemes in models like HydroGeoSphere have improved simulation accuracy but still lack full representation of FT effects on flow connectivity (Mohammed, Cey, Hayashi, Callaghan, et al., 2021, Mohammed, Cey, Hayashi, & Callaghan, 2021).

Snow and vegetation jointly regulate how water moves through frozen ground. Acting as a blanket, snow insulates the soil, sets frost depth and temperature, and steers the balance between infiltration and runoff. Thus thin snowpacks oftentimes deepens frost and favor overland flow, whereas thick snow keeps soils warmer and more permeable, promoting meltwater infiltration (Iwata et al., 2010). Vegetation reshapes these controls by trapping snow and altering surface insulation, with changes in shading, rooting, and transpiration that modify soil thermal and moisture regimes (Fu et al., 2018; S. Liu et al., 2021; Woo, 2012). Furthermore, shrub expansion in tundra has been shown to enhance snow accumulation, deepening the active layer in some regions while stabilizing it in others, depending on ground-ice content and topography (Domine et al., 2022). These divergent effects highlight the necessity of explicitly including vegetation–snow interactions in ecohydrological models. As permafrost thaws, soil moisture and groundwater tables reorganize, enabling shrub and wetland expansion that reinforces ground warming and accelerates thaw. Capturing these couplings requires watershed-scale models that integrate ecosystem and hydrologic processes (G. Hu et al., 2023). Figure 2 conceptually summarizes how these processes interact in frozen soil environments. In essence, frozen soils restrict and redirect hydrologic fluxes, acting as semi-impermeable layers and conduits upon thaw, exhibiting a behavior that underpins many of the phenomena discussed in later sections.

3. Current Progress on Frozen Soil Hydrological Processes

Recent studies have greatly improved our understanding of how frozen soils are changing over time and how hydrologic processes respond. Observations across the circumpolar north and high mountain regions indicate significant shifts in frozen ground extent and characteristics in response to climate warming.

Figure 3. The network of keyword co-occurrence (>10) in frozen-soil hydrology. Records were retrieved from Scopus on 17 January 2024 using the query: ("Frozen soil") AND ("hydrological processes") AND (modeling OR "climate change" OR agriculture OR ecology OR engineering). We limited to journal articles and reviews in English. After de-duplicating and screening for hydrology relevance, 1,217 records remained for keyword co-occurrence analysis in VOSviewer (association strength; minimum keyword occurrences = 10). Counts correspond to the screened corpus to ensure internal consistency. (a) The network highlights three clusters of research focus: "key parameters and modeling" (orange), "hydrological processes" (green), and "climate change impacts" (purple). The size of nodes reflects keyword frequency, and connections show frequent co-mention. (b) Temporal trend of publication topics (2000–2022) showing rising interest in integrated modeling and permafrost hydrology in the last decade: pre-2008 on mathematical modeling and snowmelt runoff; 2008–2018 on numerical models, infiltration/runoff, permafrost thaw, and climate change; and post-2018 on unfrozen water content, theoretical modeling, permafrost degradation, climate models, and human impacts on water quality.

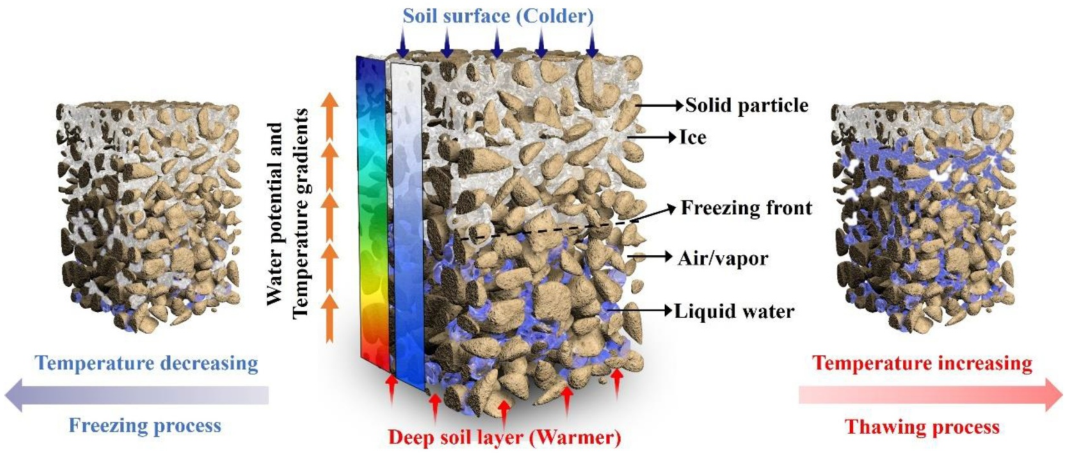

Figure 4. Coexistence of unfrozen water, air, and ice in unsaturated frozen soils. The simplified pore diagrams illustrate how liquid water (blue) remains in smaller pores due to adsorption and capillarity while larger pores fill with ice (white) as temperature drops. The right panel shows that during thawing, the percentage of liquid water in pores increases (ice melts first in larger pores and along grain contacts). These phase distributions affect both thermal and hydraulic properties of the soil.

3.1. Historical and Projected Changes in Frozen Soils

Historically, warming trends have significantly reduced soil frost depth and duration, particularly at high altitudes and latitudes. For example, seasonal frost depth on the Tibetan Plateau decreased by 4–12 cm per decade, triggering earlier spring thaw, altered runoff, and ecological shifts (Zhao et al., 2004). In northern Canada, unprecedented winter rain and melt events have caused mid-winter flooding and ice jams (Prowse et al., 2007). Satellite and ground data indicate the number of freezing days per year in the Northern Hemisphere have decreased by about -0.17 d yr^{-1} (Yuan et al., 2025), reflecting shorter seasonal freeze periods and later freeze-up/earlier thaw dates in many regions. The extent of permafrost has also measurably declined with recent syntheses showing continuous permafrost has warmed by 0.3–0.4°C per decade since the early 21st century (Biskaborn et al., 2019), and discontinuous permafrost boundaries have retreated poleward and upslope (S. L. Smith et al., 2022). Notably, high-resolution reconstructions reveal that under high-emission scenarios, up to 77% of near-surface permafrost may vanish by 2100 (D. Guo et al., 2023). These findings confirm that permafrost is one of the most sensitive climate indicators.

Rapid glacial melting and permafrost thaws are altering land cover (O. Carpino et al., 2021), by reshaping water distribution and runoff patterns (Nitze et al., 2018). Thaw rates are particularly rapid in discontinuous permafrost zones due to both vertical and horizontal heat transfer processes, significantly transforming regional hydrology (Connon et al., 2021; Wright et al., 2022). In mountain permafrost areas, new data sets reveal widespread acceleration of rock glaciers in response to warming, indicating that debris-covered ice bodies act as important, climatically sensitive cryoreservoirs with implications for water supply in semi-arid regions (Kääb & Røste, 2024).

3.2. Hydrologic Responses to Frozen Soil Changes

Soil FT states strongly control hydrological responses. In SFG areas, reduced frost depth enables earlier thaw, enhancing infiltration, moderating spring runoff peaks, and increasing soil moisture recharge (X. Wu et al., 2018). However, mid-winter thaw events may amplify winter runoff. In permafrost regions, thaw increases subsurface permeability, influencing the transition of runoff processes from surface-dominated to deeper groundwater pathways via talik formation (Figure 2; Jepsen et al., 2016; Rawlins & Karmalkar, 2024). Permafrost thaw typically increases groundwater recharge and baseflow, as has been demonstrated in regions like the Yangtze River source (Shi et al., 2020), Tibetan Plateau (Gao et al., 2018), and Yukon Basin (Jepsen et al., 2016). This transition generally stabilizes streamflow with more year-round baseflow and less extreme peaking that alters aquatic ecosystems (Michel & van Everdingen, 2006). A pan-Arctic synthesis confirms that permafrost thaw is broadly increasing groundwater contributions to streamflow across the Arctic that fundamentally enhances year-round groundwater connectivity and reduces hydrologic seasonality (Walvoord & Kurylyk, 2016). Spatial variability in permafrost and ground ice distribution (Lacelle et al., 2022) complicates predictions, with thaw causing drier upland soils (as newly opened drainage allows water to percolate; Y. Yang et al., 2013) or contributing to wetter lowland ecosystems such as wetlands and lakes (E. A. G. Schuur & Mack, 2018).

Model projections show shifts toward groundwater-dominated streamflow regimes under future warming (Gordon et al., 2022). In the Arctic, cold-season flows are expected to increase, while spring peaks become earlier and less pronounced as subsurface drainage expands (Bring et al., 2016; Koch et al., 2024). On the Qinghai–Tibet Plateau (QTP), deepening active layers reduce summer runoff in some basins, even while total annual discharge increases elsewhere due to enhanced baseflow contributions (Gao et al., 2018). Recently, Tang et al. (2023) reported that surface darkening by black carbon and dust has hastened glacier melt, perturbed regional water cycles, and heightened downstream scarcity risks. Together, these results highlight why frozen-ground processes must be represented explicitly in water-resource projections. Outcomes will still depend on local conditions, such as ice content, soil texture, and vegetation change, but the weight of evidence points to a regional transition toward more groundwater-dominated flow regimes under continued thaw (Walvoord & Kurylyk, 2016).

3.3. Differences and Links Between Hydrological Processes in Permafrost and SFG

Hydrological processes differ between SFG and permafrost due to variations in the permanence and depth of the frozen layer (Figure 2). Permafrost, which acts as an impermeable barrier below the active layer, limits groundwater recharge and emphasizes surface runoff. In contrast, SFG permits deeper infiltration and higher baseflows when thawed, briefly mimicking permafrost conditions in winter (a shallow frozen layer creating runoff over frozen ground), but this state is seasonal and reversible. Permafrost thaw, accelerated by climate change, creates subsurface pathways (taliks) that enhance year-round groundwater flow (Diak et al., 2023; Koch et al., 2024). Recent studies (e.g., Shi et al., 2020; L. Song et al., 2022), show that permafrost thaw increases baseflow and total annual runoff in Arctic catchments, while thaw in SFG areas reduces runoff by promoting infiltration and evapotranspiration. These shifts illustrate a transition from surface-dominated to groundwater-driven hydrology as permafrost degrades.

Regionally, permafrost thaw on the QTP leads to drier conditions, contrasting wetter conditions in Alaskan and Siberian Arctic wetlands (Bense et al., 2009; S. G. Evans & Ge, 2017; Farquharson et al., 2022; Hinzman et al., 2005). Figure 5 contrasts Arctic lowland versus QTP alpine settings and illustrates anticipated climate driven shifts in hydrologic partitioning. In the QTP's alpine meadows and headwaters, enhanced infiltration into deepening active layers can lower the near-surface soil moisture and reduce immediate subsequent runoff, sometimes resulting in declining streamflow observed in certain basins (X. Wu et al., 2018; Q. Yang et al., 2018). By contrast, in lowland Arctic tundra, ice-rich permafrost thaw often creates thermokarst bogs and ponds, increasing surface water storage and baseflow (A. Smith et al., 2019). Despite differences, both SFG and permafrost regulate water availability through FT cycles, with seasonal frost acting as a temporary analog to permafrost, especially under warming-induced transitions (Gao et al., 2018).

Beyond the Arctic, rock glaciers in mountain regions act as debris-insulated cryoreservoirs. A global inventory (>51,000 rock glaciers) estimates they store ~62 ± 12 Gt of water, with major contributions in the Andes and Central Asia (D. B. Jones et al., 2018). Their resilience to warming compared to clean glaciers makes them increasingly important for downstream water security. Yet, their role is rarely represented in hydrological models, representing a key research gap.

3.4. Permafrost-Groundwater Interactions and Feedbacks

The interactions between permafrost and groundwater are an emerging frontier in cold-regions hydrological processes (Lemieux et al., 2025). Climate change has increased groundwater recharge, enhanced groundwater flow, and raised baseflow contributions to streams in permafrost regions (Kuang et al., 2024; Zhao & Li, 2025). Permafrost strongly regulates groundwater movement, with continuous permafrost limiting deeper, sub-permafrost groundwater flow and discharge mainly occurring via shallow taliks or supra-permafrost pathways (Woo, 2012). In discontinuous permafrost, thawing forms extensive lateral taliks that increase hydraulic connectivity and can dramatically alter subsurface flow paths (van Tiel et al., 2024). Newly activated groundwater flow can increase heat transport that further accelerates permafrost thaw via advective heat transfer, generating a positive feedback (Connon et al., 2018; Devoie et al., 2021; J. M. McKenzie et al., 2007).

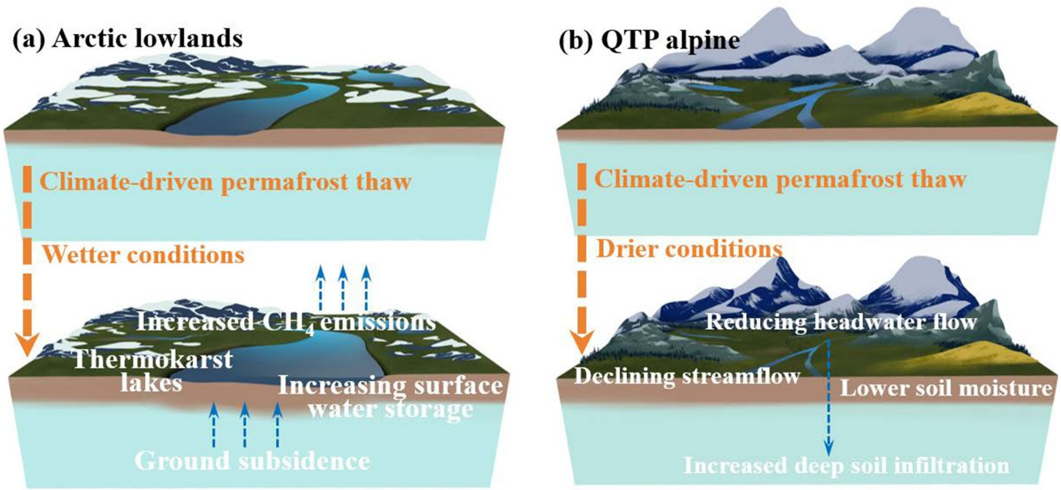

Figure 5. Contrasting hydrological impacts of thaw in (a) Arctic versus (b) Qinghai–Tibet Plateau (QTP) regions. Schematic (not to scale) of thaw impacts: (a) Arctic lowlands—subsidence and thermokarst wetting increase winter flows and CH_4; (b) QTP alpine—thaw deepens infiltration and groundwater connectivity, lowering near-surface moisture and reducing shallow headwater flow. Snowmelt occurs earlier in both; on the QTP, mid-summer runoff may decline with greater evapotranspiration and storage, reflecting climate, and topographic controls.

Despite its importance for water supply and coupling to permafrost thaw, the lack of direct groundwater measurements in permafrost areas hinders progress in resolving highly coupled processes (e.g., hydrological, geotechnical, biogeochemical). Thaw-induced groundwater dynamics significantly alter streamflow patterns, posing challenges for accurate modeling due to limited subsurface data and simplified modeling approaches (Wright et al., 2022). Identifying permafrost thaw tipping points (i.e., thresholds beyond which thaw is irreversible) is critical for predicting hydrological impacts and ecosystem transformations (Devoie et al., 2019). New geophysical imaging and isotopic tracer studies demonstrate that once taliks beneath rivers or lakes connect with regional aquifers, hydrological regimes shift irreversibly (Painter et al., 2023). Identifying such thresholds is essential for predicting landscape-scale hydrological change and its associated feedbacks.

4. Effects and Implications of Frozen Soil Hydrological Processes

Frozen soil hydrology shapes agriculture, engineering, ecology, and climate by controlling water flow, nutrient release, and soil stability (Figure 6). Rapid snowmelt infiltration can impair water quality and increase erosion, while FT cycles and greenhouse gas (GHG) emissions alter ecosystems, carbon storage, and climate feedbacks. Ice-filled pores may block infiltration, cause floods and infrastructure damage, yet also boost soil moisture for crops. Climate warming further raises soil and groundwater temperatures, threatening water resources, ecosystems, and infrastructure.

4.1. Agricultural and Soil Salinity Issues

Agriculture faces unique challenges with frozen soils due to their seasonal FT behavior and resulting effects on soil moisture and structure. FT processes affect runoff and erosion: when soil is frozen, snowmelt or rain can run off directly, exacerbating spring erosion in farmlands. Ice in soil disrupts pore size distribution, increasing erosion risk (Six et al., 2004). However, FT cycles can break up soil aggregates and reduce the soil density of the plow pan layer, increasing water infiltration into deep soil. More research is needed to quantify frost's effects on porosity and the role of soil texture and chemistry (Mohammed et al., 2018).

In agricultural peatlands, drainage of water for cultivation turns organic soils into carbon sources year-round, but water table depth (WTD) remains a key factor for greenhouse gas emissions, offering potential for emission reductions without halting agriculture. For instance, halving the WTD could potentially lower emissions by over 1% of global anthropogenic GHG emissions (C. D. Evans et al., 2021). Thaw-induced shifts in WTD remain highly uncertain: in some landscapes thaw impedes drainage and raises WTD, while in others it opens subsurface

Figure 6. Effect of freeze-thaw cycles on ecological, agricultural, engineering, and environmental practices in cold regions. Schematic example, infrastructure on permafrost experiences ground settling when ice-rich permafrost thaws (damaged road illustration).

flow paths and lowers WTD, leading to divergent outcomes for both crop viability and soil carbon balance (Walvoord & Kurylyk, 2016).

In mountainous regions, multi-cropping irrigated systems rely on snow and glacier melt to regulate seasonal river flows for agriculture (Biemans et al., 2019). Changes in frozen soil can modify these meltwater delivery patterns. Land use practices also impact heat and water distribution, particularly during snowmelt and FT cycles. For example, winter livestock grazing can alter the surface roughness and insulation, creating a layered soil/snow structure that promotes horizontal water movement during spring thawing (Zhao et al., 2016). Agrohydrology research often focuses on soil water supply and crop yields in summer time, with less emphasis on snowmelt and runoff dynamics. Practices like leaving crop residues influence snowmelt and sublimation by altering microclimates, but their effects on water cycles during snowmelt remain unclear (J. Liu & Lobb, 2021). Declining snowfall reduces the insulating effect of snow cover on winter wheat, thereby increasing yield losses from freeze injury even as warmer winters reduce extreme cold damage (P. Zhu et al., 2022). This behavior suggests that hydrological changes linked to frozen soils may offset some benefits of climate warming for agriculture.

Salinity governs freezing and coupled water–heat transfer through freezing-point depression and the thermodynamics of coexisting ice–liquid–salt phases (Rouabhi et al., 2018). Higher salt lowers water activity and depresses the freezing point (Ming et al., 2020), while FT drives water and solute redistribution that concentrates salts at the surface; irrigation can intensify this cycling by adding water and ions (Qin et al., 2021). Field studies from Northeast China show that repeated FT cycles exacerbate topsoil salinization by mobilizing salts upward, threatening crop productivity unless countered by leaching or soil amendments (Qin et al., 2021). Management therefore centers on water control: fall leaching and controlled freezing ("cryodesalination") show promise as management options. Winter saline-water freezing irrigation in the Hetao District lowered topsoil salinity and indicates a potential use of saline groundwater where freshwater is scarce, though long-term thresholds need testing (K. Guo & Liu, 2021).

4.2. Engineering Practice and Subsidence

Engineering in cold regions must contend with the challenges posed by frozen ground. SFG damages transport infrastructure as FT cycles crack pavements and de-icing salts lower the freezing point, altering freezing patterns and amplifying frost heave (Ozsoy & Yildirim, 2016). In permafrost regions, infrastructure like buildings, pipelines, and roads are vulnerable to thawing permafrost (Y. Ran et al., 2022) which causes ground settling and destabilization, leading to structural damage (Harris et al., 2009). Rapid climate change exacerbates permafrost degradation, threatening northern infrastructure with thaw slumps in ice-rich terrains (Kokelj et al., 2015) and Arctic coastal communities with shoreline loss due to warming, salinity, and sea-level rise (Creel et al., 2024; A. Gelfan et al., 2024; Nielsen-Englyst et al., 2023). Ice-rich permafrost thaws slower due to latent heat but poses greater risks of subsidence once thawed (Walvoord & Kurylyk, 2016). Recent reviews highlight that 30%–50% of Arctic infrastructure is at high risk from thaw-related damage by 2050 (Hjort et al., 2022), with projected maintenance and reconstruction costs reaching hundreds of billions of dollars.

Unevenly distributed excess ice forms lenses and wedges, causing non-uniform subsidence and thermokarst formation upon thawing. While thermokarst lakes in Arctic lowlands amplify subsidence and thaw through positive feedback, Painter et al. (2023) found these effects self-limit over time as increased runoff and evapotranspiration dries the tundra, reducing surface-atmosphere coupling and slowing subsidence. Abrupt permafrost thaw, particularly involving excess ice, can cause significant ground subsidence and ecological changes, altering hydrology. Subsidence from permafrost thaw ranges from 0.4 to 1.7 cm yr^{-1} in regions like the Mackenzie Valley and Alaska's coastal plains, reaching up to 7.5 cm yr^{-1} in Canada's High Arctic regions where sparse vegetation offers little protection (Farquharson et al., 2019; H. B. O'Neill et al., 2023; Shiklomanov et al., 2013). Thawing permafrost and newly connected aquifers further trigger seepage and flooding in once-stable corridors, threatening rail beds and culverts and demanding improved drainage and groundwater management (Kurylyk & Hayashi, 2016; X. Wu et al., 2018). However, thawing ice-rich peat causes land subsidence and thermokarst wetland formation (Fahnestock et al., 2019), significantly modifying local hydrology and nutrient cycling that are often accelerated by human disturbances and wildfires (Chadburn et al., 2017; Wright et al., 2022).

Understanding coupled thermo-hydro-chemo-mechanical soil behaviors is critical for hazard mitigation and adaptation, both in seasonally frozen and permafrost environments. Engineers mitigate these effects by using non-frost-susceptible materials, installing insulation or thermal siphons to preserve permafrost, or actively heating the ground to prevent FT cycles. Designs once assumed continuous, cold permafrost as a stable foundation, but warming now demands active thermal controls such as piles, thermosiphons, and insulation (Hjort et al., 2022). Emerging approaches emphasize dynamic adaptation, including flexible foundation design, improved surface and subsurface drainage management, and integration of permafrost monitoring into infrastructure planning (Y. Ran et al., 2022). In addition, improved hydro-thermal-salinity models can guide artificial ground freezing in coastal underground engineering and help address spatial variability in hydrothermal properties for water-rich strata (K. Q. Li et al., 2023).

4.3. Ecological Significance and Vegetation Shifts

Vegetation dynamics both shape and respond to frozen-soil hydrology, establishing coupled ecohydrological feedbacks across seasons to decades. Vegetation type, structure, and spatial pattern regulate snow accumulation/redistribution, ground insulation, frost depth, and soil-moisture regimes, thereby modulating permafrost stability and active layer thickness (ALT) (Fu et al., 2018; Z. Liu et al., 2021; Woo, 2012). Thaw-driven redistribution of water and nutrients drives compositional shifts (e.g., birch/black-spruce to wetlands and shrub-to-graminoid transitions) consistent with co-occurring boreal browning and high-latitude greening signals (O. A. Carpino et al., 2018; Verbyla, 2011). While changes to vegetation structure driven by permafrost can readily be detected via remote sensing techniques, the hydrological implications are more difficult to discern (O. Carpino et al., 2025), requiring further research to ground-truth remote sensing products.

Groundwater–surface water connectivity exerts seasonal thermal control on streams: diffuse discharge stabilizes temperatures, whereas focused discharge forms cold-water refugia for aquatic species (Kurylyk et al., 2014). However, long-term groundwater warming threatens lotic ecosystems and cold-water fish species (Kanno et al., 2014). In cases where permafrost thaw results in draining and drying of wetlands (e.g., Haynes et al., 2018), lakes (e.g., Lantz & Turner, 2015), and rivers, aquatic habitats are further at risk. However, recent evidence also links permafrost thaw to widespread wetland expansion, with significant implications for methane emissions and migratory bird habitats (Helbig et al., 2020).

Vegetation–snow interactions create bidirectional feedbacks: in shrub-free tundra, enhanced summer insulation can dampen ALT deepening, whereas snow trapping in shrublands tends to deepen ALT depending on local ice content and microtopography (Domine et al., 2022); taller canopies increase snow storage and alter recharge (Y.Wang et al., 2022; Young et al., 2020). Responses diverge with ground-ice content and topography (e.g., woody encroachment in ice-poor uplands vs. abrupt-thaw graminoid replacement in ice-rich lowlands, Heijmans et al., 2022) and across regions, from boreal/tundra biomes to alpine meadows and steppes of the QTP (Z. W. Wang et al., 2016). Together, these pathways highlight ALT as a sentinel of permafrost change and motivate the use of integrated, watershed-scale models that couple vegetation, snow, groundwater, and energy fluxes.

4.4. Environment and Water Quality

Frozen-ground dynamics regulate river and lake water quality by rerouting shallow and deep flow paths, reshaping connectivity, and mobilizing sediments and solutes (Rau et al., 2014). Thawing permafrost also opens new groundwater pathways and alters runoff regimes, thus increasing the risk of mobilizing contaminants stored at landfills, mines, and industrial facilities (T. McKenzie et al., 2021). Recent assessments reveal that permafrost regions host thousands of contaminated sites whose containment depends on frozen ground integrity, posing rising risks under current projections of climate warming (Langer et al., 2023). However, competing thermal–chemical–hydrological processes can result in opposing effects on water quality. For example, solute concentrations depress the freezing point which can increase frozen soil permeability and solute transport, while soil warming can increase microbial activity that can enhance rates of biodegradation that slow solute transport (Mohammed, Cey, Hayashi, Callaghan, et al., 2021). Representing these competing solute transport processes in

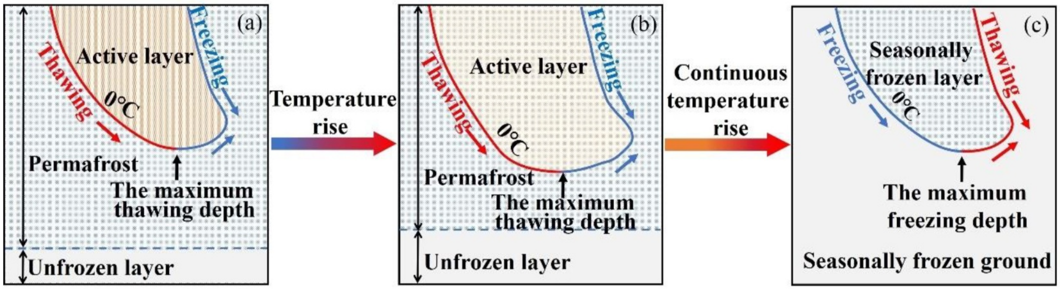

Figure 7. Schematic diagram of freeze-thaw process in permafrost region under the influence of rising temperature. (a) Current climate: thin active layer over continuous permafrost (blue). (b) Warming: thicker active layer, some permafrost converting to seasonal frost (hatched). (c) Future warming: active layer disappear, seasonally frozen layer remains with almost loss of permafrost, groundwater flows freely.

predictive models remains challenging, thereby limiting the ability to predict the effects of thawing frozen soils on water quality.

Climate-driven subsurface warming alters biogeochemical reaction rates and water chemistry, while increased groundwater–surface water connectivity from permafrost thaw increases total dissolved solids, electrical conductivity, and major-ion concentrations (Frey & McClelland, 2009) that help mobilizes geogenic contaminants such as arsenic and uranium (Skierszkan et al., 2024). Permafrost peatlands store Hg that can be microbially converted to methylmercury (MeHg), with higher production during bog-to-fen transitions (Fahnestock et al., 2019; Osterwalder et al., 2017). Alternately MeHg export likely tracks DOC-mediated transport and runoff variability (Thompson et al., 2023; Wright et al., 2022). A further pathway of carbon and water-quality change arises when reactive Fe minerals that stabilize organic carbon dissolve under reducing, water-logged thaw conditions, releasing DOC and Fe that are subsequently exported during precipitation events, as has been observed at Stordalen Mire, the Peel Plateau, and Imnavait Creek (Barker et al., 2023; Patzner et al., 2020; Thomas et al., 2023). These effects may be exacerbated by wildfire, where flow through charred soil can mobilize nutrients, carbon, and bound metals to streams, occasionally leading to eutrophication or high DOC in rivers after big fire years (Paul et al., 2022). Together, these lines of evidence argue for coupled thermo-hydrological-biogeochemical models to predict contaminant and carbon fate and to guide protection of northern ecosystems, food webs, and freshwater.

4.5. Climate Change and GHG Emissions

Frozen soils play a controlling role in coupled carbon–energy–hydrology feedbacks (E. A. Schuur et al., 2022). Permafrost thaw can increase moisture and nutrients that stimulate plant uptake, yet decomposition of newly thawed organic matter releases CO_2 and CH_4, that reinforces warming (e.g., methane-producing archaea in thawing peat) (E. A. Schuur et al., 2015). Concurrently, permafrost degradation alters snow and vegetation regimes, shifting surface albedo and atmospheric energy exchanges (Tang et al., 2023). Warming and precipitation change the dynamics of ALT and permafrost extent (Y. Song et al., 2017), reorganizing surface-subsurface connectivity, lake/soil water storage, and carbon mobilization (Bring et al., 2016; G. Wang et al., 2024) (Figure 7). Where regional heterogeneity will dictate whether areas dry with thaw (e.g., the QTP), enhancing soil oxygenation and biasing emissions toward CO_2 over CH_4 with the net radiative effect depending on the CO_2–CH_4 balance and response timescales (Jammet et al., 2017; Lewkowicz & Way, 2019). Peatlands illustrate threshold behavior, where permafrost is generally protected by the thermal properties of peat, yet once thaw is initiated rapidly landcover transitions to collapse wetlands/bogs that may release large carbon stores (Du et al., 2022; Turetsky et al., 2020; S. Yi et al., 2007) (Figure 8). Long-term flux measurements indicate winter CO_2 losses (1,662 Tg C yr^{-1}) already exceed growing-season uptake (1,032 Tg C yr^{-1}), and wildfires further add ~13.2 Pg CO_2 over 1997–2021 (X. Zhu et al., 2024). Abrupt thaw processes (e.g., thermokarst lake expansion) can greatly amplify permafrost carbon release, in some cases tripling the emissions expected from gradual thaw alone (Turetsky et al., 2020). These changes underscores why models need to represent these processes: without them, future high-latitude carbon feedbacks may be severely underestimated (Schädel et al., 2024). Including

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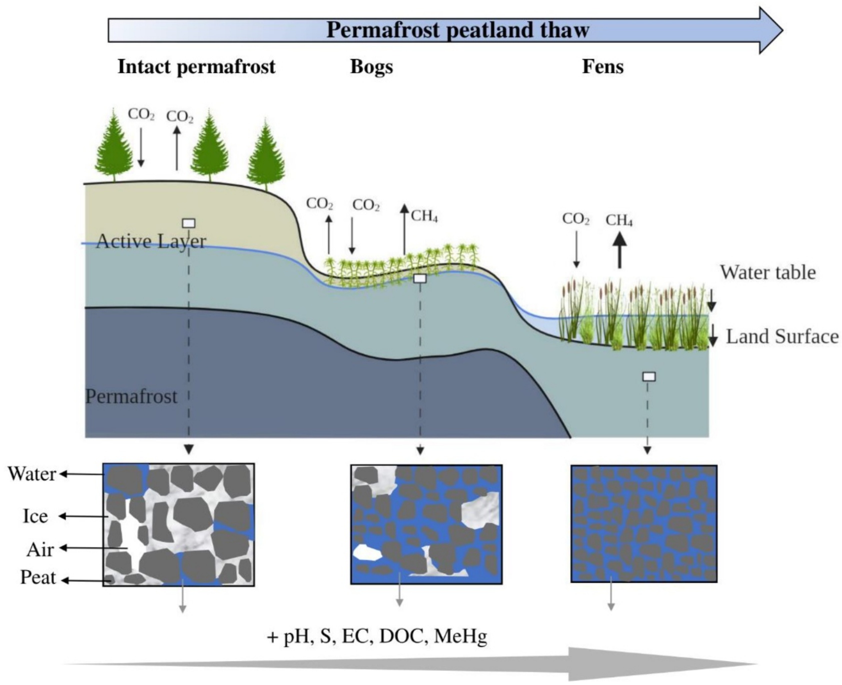

Figure 8. Permafrost peatland thaw progression showing shifts from intact permafrost to bogs (partially thawed, subsidence with water accumulation) and fens (fully thawed, inundated) and the resulting dynamics of carbon release. The diagram indicates how initially dry, elevated palsa (with permafrost) transitions to a wet bog with some permafrost, then to a fen without permafrost. Methane (CH_4) and carbon dioxide (CO_2) fluxes increase as conditions become wetter and anoxic in the bog/fen stages, while vegetation shifts from lichens and shrubs on palsas to sedges and mosses in fens. Pore water concentrations (pH; sulfur, S; electrical conductivity, EC; dissolved organic carbon, DOC), measured mercury (Hg) and methylmercury (MeHg) concentrations also change, with thaw-related wetland expansion often leading to higher MeHg production (noted by symbols).

thermokarst processes implies thaw-affected carbon release may increase up to threefold under RCP4.5 and twelvefold under RCP8.5 (Nitzbon et al., 2020).

Beyond CO_2 and CH_4, FT pulses may produce significant N_2O bursts from permafrost peatlands (Voigt et al., 2020), with additional microbial and geochemical controls (Hodgkins et al., 2014). Soil undergoes transient biophysical changes during FT and wetting-drying (WD) cycles (Figure 9), influenced by anaerobic duration, microbial sensitivity to temperature, gas diffusivity, and soil moisture dynamics. Although both cycles disrupt soil structure and increase nitrous oxide (N_2O) emissions, FT cycles often cause greater disruption due to ice crystal expansion (Denef et al., 2001). Gas solubility rises during freezing, reducing N_2O degassing, while thawing increases degassing and N_2O flux (Wagner-Riddle et al., 2010). W. Zhang et al. (2026) show that winter precipitation controls N_2O during FT cycles with low precipitation causing strong surface pulses, while high precipitation shifts N_2O to deeper soils and suppresses surface fluxes through denitrification and reduced gas diffusion. Addressing such complex phenomena requires advanced observation and modeling capabilities, which is further discussed in the next section.

5. Advances in Quantifying Frozen Soil Hydrological Processes

Recent advances have improved frozen soil hydrology research by enhancing monitoring and modeling. Techniques like advanced soil moisture sensors, continuous soil temperature profiling, and geophysical imaging have expanded capabilities to observe FT processes in situ. Meanwhile, model developments (from detailed process-based models to large-scale land surface schemes) have increasingly incorporated frozen ground dynamics.

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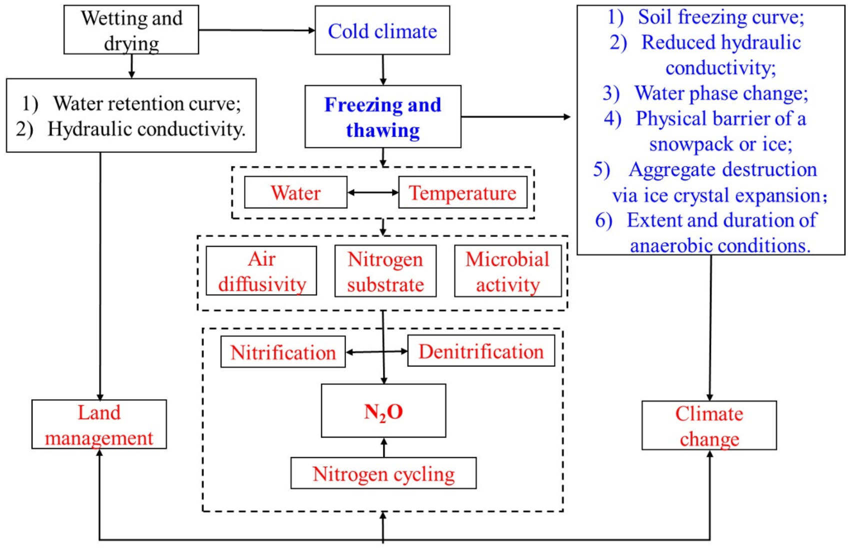

Figure 9. Model development connecting soil freeze–thaw processes and N_2O emissions. Flowchart illustrating how soil temperature (freeze-thaw cycles) influences microbial activity, gas diffusion, and water–ice distribution, which together determine N_2O production and release. Arrows indicate influences: for example, freezing creates anoxic microsites (promoting denitrification/N_2O), while thaw releases trapped gases. Model components like "snowpack module" (affecting insulation and gas trapping) and "soil organic matter module" (providing substrate for N_2O production) are highlighted. Black, blue, and red colors indicate the parameterization schemes and simulation processes applied by only wetting-drying cycles, only freeze-thaw cycles, and both cycles, respectively.

5.1. Technological Advances in Measurements of Frozen Soil Hydrological Variables

5.1.1. Frozen Soil Water Content

Frozen soil water content is now assessed with a hierarchy of methods spanning point, plot, and landscape scales, each with distinct observables, biases, and integration needs (Table 1). At the point scale, thermal-resistance temperature probes, differential scanning calorimetry, time-domain reflectometry (TDR), dual-probe heat-pulse, and nuclear magnetic resonance (NMR) have improved estimates of unfrozen water in partially frozen soils (Bittelli et al., 2003; Watanabe & Wake, 2009; X. Zhou et al., 2014). Errors often arise when ice signatures are misclassified as liquid water, motivating adaptations such as minimal-melting protocols, latent-heat-aware inversions, and numerical calibration schemes (H. He, Dyck, Si, et al., 2015; H. He, Dyck, Wang, et al., 2015; Kojima et al., 2013; Ochsner & Baker, 2008; Tokumoto et al., 2010). DPHP improves thermal inference but remains underused in peat-rich or saline settings (Zhao & Si, 2019). A new constant-temperature heat-source method further reduces probe overheating and enables robust ice-content estimation at very low temperatures (X. L. Wu & Zhao, 2024).

Because FT cycles reorganize water and ice, tracking state variables beyond volumetric water content is critical. Matric potential shows strong hysteresis between freezing and thawing phases but remains sparsely documented across soil types (H. Tian et al., 2014; Whalley et al., 2013; X. Zhang et al., 2016; Zhao et al., 2021). NMR directly partitions liquid and ice fractions, while dielectric sensors often require pairing with neutron moderation techniques to separate phases (J. Yi et al., 2014; X. Zhou et al., 2014). Salinity complicates interpretation by depressing freezing points; dielectric permittivity–conductivity models show promise in saline clays but need wider validation (H. Liu et al., 2020).

At broader scales, distributed and remote approaches bridge point data to landscape processes. Ground-penetrating radar (GPR) resolves stratigraphy and ice lenses; cosmic-ray neutron probes integrate hydrogen across tens of hectares, linking in situ sensors with satellite footprints (Mwangi et al., 2020). Passive microwave missions (SMAP, AMSR-E) detect FT transitions via emissivity changes, while active microwave sensors (scatterometers, SAR) map dielectric shifts linked to unfrozen water in permafrost terrains (Rautiainen et al., 2016; G. H. Zheng et al., 2019). Distributed temperature sensing (DTS) and active-heated fiber optics provide high-resolution spatiotemporal records of freezing fronts (Seyfried et al., 2016; B. Wu et al., 2021).

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Table 1
Summary of Different Methods Measuring Soil Moisture in Frozen Soil

Method	Measurement principle	Strength	Determining ice water	Spatial scale	Reference
Time domain reflectometry (TDR)	Difference dielectric constant of the soil and its moisture content	Deep, accuracy, non-destructive, and in situ measurement technique, but sensitive to soil salinity	Indirectly	From ~0.1 to ~1 m	Zhou et al. (2014), He, Dyck, Si, et al. (2015), He, Dyck, Wang, and Lv (2015)
Nuclear magnetic resonance (NMR)	Nuclear magnetic signal	Accuracy, deep, instant, and in situ measurement technique	Directly	From ~0.1 to ~1 m	Watanabe and Wake (2009)
Heat pulse method	Heat dissipation method, measuring temperature response of the sensor varies according to the amount of water near the porous ceramic cylinder	Accuracy, deep, non-destructive, and in situ measurement technique. Site-specific calibration	Indirectly	From ~0.1 to ~1 m	He, Dyck, Si, et al. (2015), He, Dyck, Wang, and Lv (2015)
Cosmic-ray neutron method	Measuring fast neutron intensity near the ground, the negative correlation between fast neutron intensity and hydrogen near the surface	Non-invasive, real-time, and mesoscale measurement. The footprint is about 300 m. An average soil moisture content over a certain depth (typically up to 30 cm)	Indirectly	From 100 m to 10 km	Wu et al. (2024), Mwangi et al. (2020)
Satellite Remote Sensing	Both active and passive instruments, and other sensors to determine surface soil moisture condition	Large-scale, temporal frequency measurement. The data can be integrated with hydrological and climatic models to improve predictions and analyses. But low spatial resolution, and only measurements surface soil moisture (0–5 cm)	Indirectly	From 1 to 100 km	G. H. Zheng et al. (2019), Jiang et al. (2020)

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Frequency-domain reflectometry can outperform traditional TDR in partitioning ice and liquid water (Bittelli et al., 2004). Water-potential approaches (Chuvilin et al., 2022) and unmanned aerial vehicle (UAV) platforms (Nakata et al., 2021) are emerging, further diversifying the toolkit for mapping frozen soil moisture.

5.1.2. Active Layer Thickness and FT Dynamics

Monitoring ALT and its dynamics has also advanced rapidly (Clayton et al., 2021). Conventional methods, such as mechanical probing and borehole thermistor arrays, remain reliable for point data but lack spatial continuity. Geophysical surveys now fill this gap where electrical resistivity tomography (ERT), electromagnetic induction (EMI), and seismic refraction provide continuous profiles of subsurface FT states. GPR and EMI are particularly useful for delineating shallow permafrost: GPR identifies dielectric contrasts between frozen and unfrozen layers, while EMI tracks bulk conductivity variations. If the mapped layer refreezes completely in winter, it represents the ALT (Devoie et al., 2023). While ERT produces detailed vertical sections, it is labor-intensive and GPR signals can be attenuated in clays and saline soils. Time-Domain Electromagnetics (TDEM) extend depth resolution, while surface NMR, especially when combined with TDEM, can successfully map taliks beneath thermokarst lakes or permafrost bodies (Minsley et al., 2012). Satellite interferometry (e.g., InSAR) now provides centimeter-scale detection of seasonal subsidence and long-term thaw, enabling regional assessments of permafrost stability (Zhong et al., 2021). Integration of UAV LiDAR with InSAR further enhances the ability to monitor permafrost thaw evolution.

Regional-scale integration remains a key challenge. Recent approaches combining cosmic-ray neutron sensing, fiber-optic DTS, and satellite microwave products demonstrate the potential for multi-platform fusion to scale point measurements to regional predictions (H. Jiang et al., 2020; Mwangi et al., 2020). Large-scale initiatives, including NASA's Arctic Boreal Vulnerability Experiment and national permafrost observatories, are integrating field-based and remote sensing methods to track ALT over extensive transects (Hubbard et al., 2013). Such data sets are critical for calibrating and validating remote sensing products and constraining ALT models. Complementary laboratory and tracer studies continue to refine process understanding. Together, these methods represent a rapidly expanding toolkit for frozen-soil monitoring, advancing both fundamental understanding and predictive modeling of permafrost change.

5.2. Modeling Thermo-Hydrologic Regime of Frozen Soil

5.2.1. Models Describing the Movement of the Freezing/Thawing Front (Stefan Problem)

Predicting the position of the freezing or thawing front, the moving boundary between frozen and unfrozen soil, has long been treated with Stefan-type formulations that balance latent heat against conductive heat flux under idealized, one-dimensional conditions and a sharp phase boundary (Koren et al., 1999; Woo et al., 2004). These analytical solutions are valuable for first-order estimates of frost/thaw penetration and for model benchmarking, but their assumptions (e.g., uniform soil, purely conductive heat transfer, negligible unfrozen water) are often violated in natural settings. The zero-curtain phenomenon, where latent heat buffering maintains temperatures near 0°C for days to weeks, further departs from purely conductive behavior; during this interval non-conductive heat transport can be quantified with the Péclet number (Pe) (Kurylyk et al., 2014; Yu et al., 2018). Consequently, unmodified Stefan predictions can misestimate ALT and thaw timing under stratified and/or advective conditions (Kurylyk & Hayashi, 2016).

Laboratory and field studies show that temperature gradients and cryosuction drive liquid water (and vapor) toward the freezing front, redistributing moisture and altering hydraulic/thermal properties as pore ice accumulates (Jame & Norum, 1980; H. Ran et al., 2019; Singh & Chaudhary, 1995). To represent this coupling, nonlinear Stefan formulations and numerical schemes have been developed that allow moisture migration to the freezing front. In practice, ALT is still frequently estimated from Stefan/Neumann solutions for 1-D conduction, but errors arise from heterogeneity, layered media, and variable surface energy balance (Kurylyk & Hayashi, 2016). Extensions include distributed applications (e.g., Kolyma basin runoff modeling; Kuchment et al., 2000), two-directional solutions that better handle FT cycles (Woo et al., 2004), and analytical or semi-analytical uses for parameter inference and sensitivity (G. Hu et al., 2016; J. B. Li et al., 2021; Semenova et al., 2014; Sun et al., 2020). These approaches improve realism but still struggle when advective heat transport and phase-dependent hydraulics dominate.

Modified Stefan formulations now incorporate sensible heat storage and phase-dependent hydraulic properties, yielding better agreement with observed thaw depths (G. Hu et al., 2016). Enthalpy-based (e.g., apparent heat-capacity) methods are increasingly standard in land surface models such as CLM and Noah, allowing gradual phase change representation while maintaining numerical stability (Hansson et al., 2004; Oleson et al., 2013; Yokohata et al., 2020). These methods accommodate gradual phase change and unfrozen water but require careful smoothing, calibration of phase functions, and (ideally) inclusion of advective heat due to liquid/vapor flow. In practice, our recommendations are: (a) use classical Stefan solutions for screening, diagnostics, and controlled cases; (b) use corrected/extended Stefan for basin-scale coupling when data are limited; and (c) use enthalpy-based or fully coupled heat-and-mass models when $Pe \gtrsim 1$, strong heterogeneity exists, or zero-curtain dynamics and moisture redistribution control energy closure. Systematic evaluation against multi-year ground temperature, moisture, and flux observations remains essential to quantify uncertainty and guide model selection.

5.2.2. Models Describing Coupled Water and Heat Transfer in the Frozen Soil Column

Over the decades, the research community has developed a suite of process-based hydrologic models to represent FT effects on infiltration, runoff, and subsurface flow (Table 2). Two main models describe coupled water and heat transfer in frozen soil. The mechanistic model focuses on viscous liquid flow and heat balance in porous media, often referencing the Philip-Vries model for simulating water and temperature redistribution (Bonacina et al., 1973; Harlan, 1973; Motovilov, 1977). The thermodynamic model emphasizes equilibrium states and phase changes, driven by temperature and water pressure gradients, using principles of irreversible thermodynamics (Kay & Groenevelt, 1974; Spaans & Baker, 1996). However, the Clausius–Clapeyron relation is valid only near 0°C as continual water flow in freezing soils disrupts equilibrium, invalidating its use for moisture migration (Peng et al., 2016). Contemporary implementations blend these views by coupling Richards-type flow with energy conservation and temperature-dependent phase change, and by using soil-freezing characteristic curves to relate ice content to temperature and matric potential, thereby representing capillarity, cryosuction, and permeability loss across the freezing front.

Many early models extended classical soil physics to freezing conditions by incorporating the phase change of water into Richards' equation and heat transfer equations. Several one-dimensional models simulate coupled water and heat processes in freezing soil column, for example, SHAW model (Flerchinger & Saxton, 1989), COUP model (Jansson, 2012), and HYDRUS-1D (Hansson et al., 2004). SHAW accounts for liquid, solid, and gaseous water effects on hydrothermal transfer and adjusts freezing temperatures using water potential equations, thus capturing how soil tension and ice content interact. COUP simulates water, heat, carbon, and nitrogen fluxes in the soil-plant-atmosphere system, incorporating ice effects on water transfer (Jansson & Karlberg, 2004) and uses automated calibration for parameter uncertainty (X. Wu et al., 2018). HYDRUS includes a freezing module with hydraulic conductivity adjustments for blocking effects, and its formulation has been widely applied to investigate freezing front advancement and thaw consolidation in soils (Zhao et al., 2016; C. Zheng et al., 2021). Lastly, tracer-aided models integrate isotopic and geochemical tracers to separate snowmelt from rainfall and validate flowpath partitioning in partially frozen catchments (A. Smith et al., 2019). Recent intercomparisons (Bui et al., 2020; Grenier et al., 2018) highlight systematic differences between simulators, emphasizing the need for benchmarking against field data sets (Nicolsky et al., 2007).

5.2.3. Modeling the Frozen Soil Hydrologic Cycle at a Large Scale

Scaling from point-scale process models to basin or regional predictions requires representing lateral flow, groundwater exchange, heterogeneous FT states, and tight feedbacks with the surface energy balance (Aas et al., 2019; King et al., 2020). Intercomparisons of thermo-hydrologic codes (e.g., SUTRA, COMSOL, ATS) show broadly similar patterns but may display systematic divergences arising from discretization choices, freezing curves, and governing-equation closures (Grenier et al., 2018). Many simulators still rely on external 1-D surface schemes (e.g., SHAW) or assume saturated conditions (e.g., SMOKER); fully integrated models (e.g., ATS) are computationally demanding, whereas others simplify soil freezing (e.g., HydroGeoSphere). Solute-transport implementations (e.g., IHTSM; L. Zhang et al., 2021) often omit explicit FT kinetics and cryo-chemistry, limiting realism for contaminant mobilization and carbon–permafrost-thaw feedbacks (Langer et al., 2023). The bottlenecks are scale-aware parameterizations of cryosuction, macropore/preferential flow, and hysteretic hydraulic properties, plus rigorous benchmarking against analytical cases and field data for nonlinear, path-dependent systems.

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Table 2
Summary of Different Models Describing Coupled Water and Heat Transfer in Cold Regions

Model	Application	Strength	Validation	Reference
SHAW	Simulating the interrelated heat, water and solute transfer through snow, residue and soil	Integrating detailed physics of snow, residue or soil surface to a specified depth into one simultaneous solution	Six diverse tillage-residue conditions of the USDA Plouse Conservation Field Station	Flerchinger and Saxton (1989), Kojima et al. (2013)
COUP	Simulating water, heat, carbon, and nitrogen fluxes in the soil-plant-atmosphere system	Flexible to set up the simulation time-step and the thickness of soil layers and capable of conducting uncertainty analysis	Different irrigation districts in China	Wu et al. (2021), Jansson (2012)
Hydrus-1D	Simulating liquid and vapor flow driven by both thermal isothermal forces	Well-designed, user-friendly GUI and various complementary features (e.g., parameter optimization routines and flexible boundary conditions)	Bare field in the Mu Us Sandy Land	C. Zheng et al. (2021), Hansson et al. (2004), Zhao et al. (2016)
IHTSM	Simulating the coupled water, heat, and solute migration under unidirectional freezing conditions	Providing references for the destruction process analysis of the harsh geological environment in cold, arid, and saline areas	A silt soil column	X. Y. Zhang et al. (2021)
STEMMUS	Investigation of the mechanism of water, vapor, and air flow of freeze-thaw processes	The interactive effect of soil ice and air pressure on the vertical variations of advective liquid/vapor fluxes in frozen soils can still be recognized	Alpine meadows site of the Tibetan Plateau	Yu et al. (2018), Zeng et al. (2011)
COMSOL	Considering the coupled process of liquid water, water vapor, and heat transport	Calculating the coupled soil mass and energy budget	Field site between Fenghuo Mountain and Kekexili Volcanic area in the Tibetan Plateau	X. Zhang et al. (2016)

Representing soil structural change is equally limiting. Cryoturbation reorganizes pores, transports fines, and nucleates ice lenses that control hydraulic connectivity. Hydro-thermo-mechanical formulations link void ratio, stress–deformation, saturation, and lens growth while identifying thermally driven cryosuction as the dominant driver of water migration to the freezing front (Huang & Rudolph, 2021; Lai et al., 2014). These advances underscore a prerequisite for credible active-layer dynamics: accurate surface-energy partitioning and temperature gradients, which in turn demand realistic albedo, aerodynamic roughness, and temperature-dependent thermal properties of partially frozen media.

Land-surface and semi-distributed hydrological models remain powerful tools for simulating cold regions processes at large scales. Snowmelt modules Variable Infiltration Capacity (VIC) and Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Liang et al., 1994) have been refined, with independent ice/snow algorithms recommended for SWAT-class models (Q. Li et al., 2021), while CRHM and ECOMAG embed more explicit FT physics for cold basins (A. Gelfan et al., 2017; Pomeroy et al., 2007). Climate-oriented land surface models (LSMs; e.g., CLM, Noah, VIC) now include permafrost hydrology (Lawrence & Slater, 2008; Niu & Yang, 2006; Oleson et al., 2013), yet coupling of vapor fluxes and unfrozen water remains incomplete. New intercomparisons show that land-surface models in CMIP6 still underperform in reproducing permafrost thermal dynamics, partly due to simplified soil physics (Burke et al., 2020; G. Hu et al., 2023). Pragmatic adaptations often implement two-layer representations, like the HBV model with an infiltration-limited active layer (Lindström et al., 2002) and distributed runoff schemes with impermeable frozen layers (Kuchment et al., 2000). However, emerging tools are helping to bridge scales: assimilating satellite FT states to better constrain soil temperature and runoff, using artificial intelligence (AI) emulators to capture subgrid preferential flow, and applying tracer-aided models to resolve water ages and mixing (Piovano et al., 2019; A. Smith et al., 2019).

Recent advances in remote-sensing–derived river discharge provide powerful constraints for cold-region hydrologic modeling and DA. For example, pan-Arctic discharge products based on satellite imagery and machine learning (ML) reveal changes in freshwater export and freshet timing that can be assimilated to constrain winter/baseflow contributions under thaw (Feng et al., 2021). Similarly, high-resolution analyses over High Mountain Asia show accelerating discharge on a subset of rivers, implying evolving melt–runoff partitioning that DA can capture in cryo-impacted basins (Flores et al., 2025). In practice, integrating these data via ensemble-based or variational DA with cold-region land/hydrologic models should improve representation of FT-controlled permeability, taliks, and seasonality, especially when paired with microwave FT status and groundwater indicators.

Meta-analyses emphasize a persistent divide between surface-focused models and fully coupled subsurface thermo-hydrology (Bui et al., 2020; Grenier et al., 2018). A practical path forward is a tiered framework: (a) 3-D process models for mechanism discovery and parameter priors; (b) intermediate-complexity, cryo-aware models with transferable parameterizations for regional forecasting; and (c) continental LSMs with structural ensembles and systematic benchmarking using remote sensing and isotope/tracer constraints. This hierarchy, coupled with shared testbeds and intercomparisons, enables defensible basin-to-continental prediction under continued warming.

5.2.4. Modeling Greenhouse Gas (CO_2, CH_4, N_2O) Emissions in the Frozen Soil

Permafrost-enabled land models (including CMIP6-class ESMs) now simulate high-latitude CO_2 and CH_4 release from thawing soils. However, such models remain limited in reproducing present-day soil-carbon stocks, turnover, and feedbacks, which propagates large uncertainty into projections (Natali et al., 2021; E. A. Schuur et al., 2022). Most models stratify soil carbon by depth and parameterize decomposition as functions of temperature, moisture, and oxygen; methane (CH_4) submodules typically represent anoxic production, aerobic oxidation, and transport via diffusion, ebullition, and plant aerenchyma. Despite model performance being highly sensitive to wetland extent, many models still use static or satellite-derived masks, while only a minority predict wetlands prognostically from water-table/topographic constraints (TOPMODEL-type). Additionally, emerging data-driven products (e.g., WAD2M) and ensembles (e.g., WetCHARTs) reveal large heterogeneities in seasonal cycles and climate sensitivities (Bloom et al., 2017; Gedney et al., 2004; Saunois et al., 2020; X. Y. Zhang et al., 2021). Critically, most frameworks under-represent abrupt thaw features (thermokarst lakes, collapse-scar bogs) that rapidly expand saturated area and amplify CH_4 release (Turetsky et al., 2020; Walter Anthony et al., 2018). Representation of N_2O is even more rudimentary: many models apply generic nitrification/denitrification parameterizations and miss FT pulses and thermokarst "hot spots" despite syntheses showing substantial fluxes from permafrost-affected soils (Voigt et al., 2020).

FT cycles reorganize moisture and redox, driving episodic N_2O bursts (Voigt et al., 2020) that are poorly captured when models rely on smooth temperature scalars. Accurate prediction requires observations that resolve snow–soil thermal regimes and gas transport, since diffusivity through snow/ice modulates efflux and wind pumping can drive non-Fickian exchange in amounts that exceeds Fickian diffusion (Seok et al., 2009). For example, the release of physically trapped N_2O during melt explains observed winter spikes but contributes little to annual fluxes (Risk et al., 2014). Additionally, frozen matrices suppress O_2 diffusion and nitrification/denitrification (Teepe et al., 2001), whereas FT pulses transiently stimulate N_2O (X. Li et al., 2021; Wolf et al., 2010); model performance improves, however, when moisture/structure predictors are used (Congreves et al., 2018). Linear temperature-response schemes underestimate FT-driven N_2O in croplands by ∼17%–28% and overestimate colder grasslands (Del Grosso et al., 2022; Wolf et al., 2010). Widely used models (DayCent, DNDC) still lack predictive algorithms using explicit FT microphysics and/or rely heavily on soil-temperature parameterizations, whereas adding frozen-soil heat transfer improves winter soil temperature predictions and N_2O simulations (Del Grosso et al., 2022).

Deeply coupling GHG modules with hydrology is essential to narrow uncertainty in permafrost feedbacks. Linking land-surface/climate models to subsurface heat and groundwater flow (i.e., capturing conductive and advective heat transport) improves soil thermal realism, the space–time placement of CO_2/CH_4 fluxes, and prediction of hydrologic convergence zones (valley bottoms, connected wetlands) that thaw earlier and emerge as methane hot spots (Walvoord & Kurylyk, 2016). Community intercomparisons show fully coupled, multiphase simulators resolve phase change and heat–mass transfer better than simpler schemes, though at higher computational costs (Grenier et al., 2018), and that surveys better confirm gaps between surface-oriented and subsurface-oriented models (Bui et al., 2020). Multi-model assessments indicate higher levels of confidence in CO_2 projections (largely scales with thawed-carbon amount) than in CH_4 and N_2O emissions, where uncertainty hinges on hydrology, dynamic wetland formation, and under-represented FT microphysics (Del Grosso et al., 2022; Natali et al., 2021). Priorities include parameterizations for abrupt thaw and wildfire effects, groundwater-mediated heat transport, and emergent wetlands. The parameterizations should be supported by coordinated observation–model integration to evaluate model performance and communicate risks.

5.3. Parameterizations Schemes for Frozen Soils

Parameterization schemes are utilized to mathematically represent the physical and chemical processes that occur within frozen soils. Their purpose is to provide the values of model parameters or simplified formulations that capture the essence of complex processes (like phase change, flow impedance, etc.) without resolving them in full detail. It is crucial to utilize suitable parameterization schemes, as omitting or mis-specifying parameters can result in larger errors and uncertainty in simulating soil temperature and moisture (W. Hu et al., 2025; Pitman et al., 1999). Poor or missing frozen-ground parameterizations can amplify soil temperature biases and misrepresent the effects of winter on soil cooling (Viterbo et al., 1999). In light of these findings, past parameterizations for key processes in frozen soils have been summarized (Figure 10).

5.3.1. Freeze-Thaw Parameterization Schemes

FT parameterization generally falls into three families (Q. Yang et al., 2018): (a) binary threshold approaches that switch soil water to ice when temperature falls below 0°C; (b) empirical unfrozen water relations that link temperature to matric potential via power law fits; and (c) physically motivated freezing point depression formulations, widely implemented in SHAW, Noah, and CLM. While complexity rises across these families, so do data and computational demands; the simple scheme is robust but can misrepresent partial freezing, whereas empirical curves improve realism yet suffer from limited transferability across textures and salinity regimes (W. Hu et al., 2025). Recent updates incorporate supercooled liquid water, hysteresis, and phase change enthalpy (Lan et al., 2015) that improves the accuracy of soil temperature and moisture simulations. Persistent challenges include parameter identifiability, reconciling point scale calibration with landscape heterogeneity, and reproducing diurnal/late winter ground temperature variations that control infiltration and runoff. Progress will likely come from hybrid schemes and data assimilation that constrain parameters with multi sensor observations.

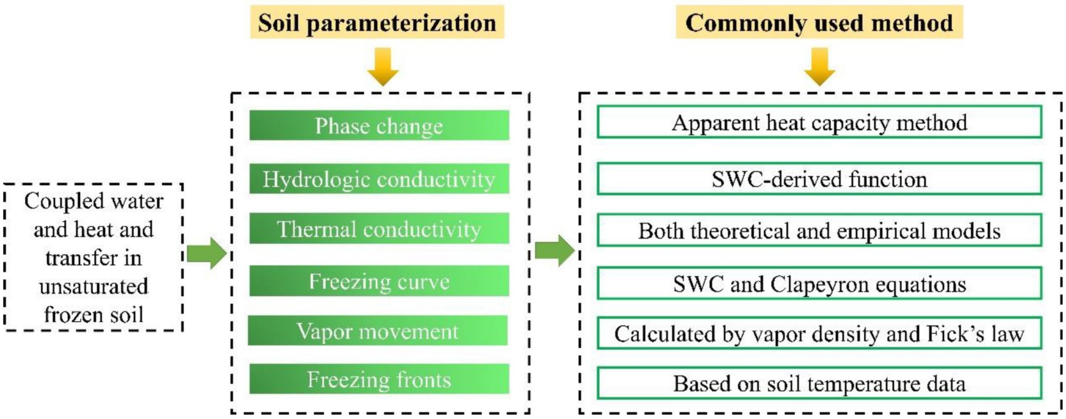

Figure 10. Summary of key parameterization schemes for frozen soil processes in models.

5.3.2. Phase Change

Phase change is represented by coupling latent heat to a soil specific freezing curve that partitions phases and controls apparent heat capacity and hydraulic impedance. Two implementations are used: (a) an apparent heat capacity/enthalpy scheme that spreads latent heat over a small temperature range; and (b) an explicit latent heat source with prognostic ice content that is solved when fully coupled with Richards flow equation and/or operator splitting. For rapid freezing, supercooling, or ice lens growth, a non-equilibrium relaxation of the freezing curve allows departures from thermodynamic equilibrium. All terms are energy-mass consistent and reconcile with vapor condensation and deposition, avoiding double counting. The apparent heat capacity method neglects unfrozen water (Sun et al., 2020), whereas the enthalpy method simplifies phase change but poorly separates liquid and ice in partially frozen soils, often assuming constant unfrozen water (Bao et al., 2016).

5.3.3. Hydraulic Conductivity

Hydraulic conductivity in frozen soils declines as ice occludes pores, altering size, tortuosity, and connectivity (L. Zhang et al., 2021). A practical parameterization treats effective conductivity as the product of a temperature-dependent saturated term (reflecting viscosity), a relative-permeability term linked to unfrozen water saturation from the soil-freezing/retention curve, and an ice-impedance factor that reduces flow via power-law or exponential functions of ice content (e.g., Zhao et al., 2013). Anisotropy and time-evolving saturated conductivity can represent lensing, FT damage, and hysteresis. Where macropore pathways matter during melt, a dual-domain blend of macropore and matrix conductivities is applied. Existing approaches span semi-theoretical capillary/sorptive formulations, empirical temperature relations, and water-content-based rules, but performance degrades at low temperature and high ice content (Watanabe & Wake, 2009). Recent schemes, modified van Genuchten formulations, and dual-porosity models, improve fits yet require validation across soils and temperatures (Nicolsky et al., 2007; Y. Zhang et al., 2008; L. Zhang et al., 2021).

5.3.4. Thermal Conductivity

Soil thermal conductivity is best represented as an effective property governed by the liquid-, ice-, and air-filled pore fractions, texture/mineralogy, bulk density/porosity, and organic content. Mixing-model approaches are widely used (e.g., Johansen/de Vries with Kersten-type saturation factors) and separate parameterizations for frozen versus unfrozen states. Latent-heat effects are handled via an enthalpy/apparent-heat-capacity scheme with a narrow smoothing near 0°C to align with unfrozen-water curves and avoid double counting. Optional anisotropy captures layering and ice lenses, and snow–soil thermal contact is treated consistently. Model formulations span theoretical/mathematical and empirical families, and hybrid schemes combine physical theory with accessible soil data (Abu-Hamdeh & Reeder, 2000; Dong et al., 2015; Zhao et al., 2021). A key challenge is the strong nonlinearity around freezing: small ice fractions sharply raise conductivity through particle-bridging, whereas further freezing yields diminishing returns. Many land models still rely on lookup tables or simple liquid/ice functions, underscoring the need for continued laboratory validation under FT conditions.

5.3.5. Freezing Curve

The soil freezing characteristic curve (SFCC) is typically parameterized by linking temperature to suction through the generalized Clausius–Clapeyron relation, combined with soil water characteristic curves (SWCC). When direct observations are limited, monotonic empirical functions constrained by TDR, NMR, or gamma attenuation are applied, with separate freezing and thawing branches to capture hysteresis. The temperature sensitivity of ice content provides the latent heat term in apparent heat capacity or enthalpy formulations and informs unsaturated hydraulic conductivity; consistency with ice-impedance multipliers must be maintained. Water and heat movement in partially frozen soils further depends on hydraulic and thermal conductivities together with SWCC and SFCC, both of which show hysteresis. Early formulations (Harlan, 1973) often overestimated fluxes, but later models such as SHAW, HYDRUS, and COUP incorporate impedance factors to reduce bias (Hansson et al., 2004; Jansson & Karlberg, 2004). Recent advances extend SFCCs to saline soils and incorporate solute exclusion, improving applicability under climate change (Amankwah et al., 2021; Bi et al., 2023; Devoie et al., 2022; Y. Zhou et al., 2019).

5.3.6. Frozen Soil Infiltration

Accurate parameterization of infiltration during freezing and thawing is critical for simulating runoff generation in cold regions (Appels et al., 2018; Quinton & Marsh, 1999). Common schemes include (a) reducing hydraulic conductivity with increasing ice content ("impedance factors"), (b) assigning a frozen-impermeable surface fraction, (c) disabling infiltration beyond a critical ice threshold, and (d) dual-domain formulations that permit macropore bypass during snowmelt (R. Jiang et al., 2024). Some models also couple infiltration capacity to the depth and migration of the FT front. Process performance depends on soil texture, antecedent moisture, cryostructure, and melt intensity as thin, discontinuous ice can admit limited percolation, whereas connected lenses force Hortonian overland flow (Z. He et al., 2023; Sanchez-Rodriguez et al., 2025). Because freezing and thawing exhibit hysteresis and strong subgrid variability, robust schemes tile the landscape or apply probabilistic frozen-area approaches and calibrate jointly to soil temperature–moisture profiles and event hydrographs. Where frozen layers host cracks or biopores, enabling preferential bypass is essential to reproduce early-season freshet peaks without inflating late-season runoff.

5.3.7. Vapor Movement

In frozen soils, vapor transport becomes the dominant pathway because liquid flow is impeded. Two mechanisms, isothermal and thermal vapor diffusion, are represented with an effective diffusivity scaled by air-filled porosity and tortuosity, with optional enhancement for non-ideal transport. Condensation or deposition near freezing fronts is coupled through latent heat, while maintaining energy–mass consistency (unfrozen water curve, apparent heat capacity), shaping temperature profiles and the timing of infiltration–runoff partitioning under winter conditions and at the snow–soil interface. During freezing, unfrozen water migrates toward the freezing front under reduced water-pressure gradients, producing sensible and latent heat transfer. Once fully frozen, vapor dominates in the shallow vadose zone at low water potentials (C. Zheng et al., 2020). Recent studies including liquid, vapor, and air fluxes show minimal liquid–vapor advection, but ice–air interactions can alter advection, and direct vapor measurements remain difficult. Therefore, Fickian estimates based on vapor density are often applied (Yu et al., 2018).

5.3.8. Freeze-Thaw Fronts

FT fronts are commonly represented by three strategies: Stefan-type degree-day schemes, apparent heat-capacity formulations that distribute latent heat over a narrow temperature interval, and explicit front tracking with interfacial mass/energy balance. These choices govern the timing and depth of infiltration shutdown, cryosuction, and latent-heat buffering at advancing/receding fronts (Z. Xie et al., 2018). Parameterizations of soil layering/stratification strongly modulate water-table fluctuations and surface evaporation (Koirala et al., 2014). Diagnostic approaches that infer front position from soil-temperature profiles are practical but prone to numerical oscillations. Semi-empirical options, such as the Stefan model (Woo et al., 2004), FT index model (Nelson & Outcalt, 1987), and Kudryavtsev model (Nan et al., 2012), all provide parsimony, yet the first two omit non-conductive heat transfer and soil-moisture variability, whereas the Kudryavtsev formulation, though more comprehensive, yields larger uncertainty in active-layer thickness. These trade-offs motivate hybrid, data-constrained schemes that couple physically based heat-water-vapor transport with computationally efficient front metrics.

6. Future Research Directions

Frozen soil hydrological processes critically influence water and energy cycles in cold regions, shaping how climate change impacts manifest and contribute to large-scale feedbacks. While current models and observations have advanced our understanding, several important directions remain for future research.

6.1. Data Scarcity and Networks

Urgent expansion of integrated frozen-soil monitoring is needed across cold regions, where vast areas, especially the Russian and Canadian Arctic and alpine zones of Asia and South America, lack observations of soil temperature, moisture, active-layer dynamics, and winter processes (Harris et al., 2009). Strengthening programs (e.g., GTN-P and an emerging Global Seasonal Frost Zone network) and open synthesis of ALT and under-snow moisture would provide validation targets and reveal accelerating ground-ice loss. Because no single method fully captures both liquid water and ice content, combined approaches (e.g., TDR with cosmic-ray neutron probes, DTS with UAV-based sensing) should be prioritized (Z. C. Tian et al., 2020). Remote-sensing accuracy varies with soil, vegetation, and elevation, so ground networks must be integrated with satellites. ML-assisted data fusion shows promise in integrating heterogeneous data sets, from isotopes to geophysical imaging, to fill observational gaps (Baghbani et al., 2022).

6.2. Scaling and Integration

Bridging scales remains a core challenge, from pore-scale physics to catchment hydrology and global climate (Rodenhizer et al., 2023). Progress hinges on upscaling ice-lens formation, preferential flow, and heterogeneous thaw via better sub-grid parameterizations and nested frameworks. Although models now couple soil thermal, hydrologic, and atmospheric processes, scaling and data-assimilation hurdles persist (Bao et al., 2016; van Tiel et al., 2024). More integrated observations, such as combining flux towers, deep soil/permafrost measurements, and remote sensing, are needed to help constrain scale transitions (Virkkala et al., 2021). There also continues to be uncertainty in parameterizing frozen soil models due to spatial heterogeneity (Ireson et al., 2013). While calibration (GLUE, Bayesian, Monte Carlo) and AI optimization can reduce the uncertainty, there is still a need for stronger validation and higher quality inputs (Duan et al., 2007; Gupta et al., 2023; M. Wu et al., 2019). Nested approaches show promise (Z. He et al., 2023), but simulation of water, heat, and macropore dynamics requires theory and rigorous validation (Kurylyk & Watanabe, 2013; Mohammed, Cey, Hayashi, Callaghan, et al., 2021). Additionally, many models omit non-conductive heat and vapor fluxes (G. Hu et al., 2023) despite its importance in accurately predicting thaw. To aid in resolve scaling and uncertainty issues, multi-physics frameworks that integrate remote sensing and field observations are needed to improve projections of permafrost thaw and hydrologic responses to climate warming (e.g., tele-connected effects) (Tang et al., 2023).

6.3. Permafrost-Carbon-Hydrology Feedbacks

Coupling water and carbon under permafrost thaw requires integrated research across geomorphology, hydrology, and biogeochemistry. Predicting where thermokarst lakes develop and persist is essential because they reshape the local hydrology and act as hotspots for CH_4 emissions. Thaw-induced pulses of nitrogen and phosphorus can drive eutrophication and/or nutrient uptake depending on hydrological flow paths (Walvoord & Striegl, 2007), while "ghost nutrients" such as legacy nitrate or mercury may be remobilized as drainage networks reorganize under warming. Uneven thaw produces wet-dry mosaics in which frozen uplands collapse into wetlands, expanding surface water, lowering albedo, and altering evapotranspiration and carbon uptake (Helbig et al., 2020). FT cycles regulate root mortality and soil fauna (Sorensen et al., 2018), yet winter bio-hydrological mechanisms remain poorly resolved. Vegetation shifts feed back on soil thermal regimes, further complicating prediction of carbon fluxes. Abrupt thaw rapidly transforms energy balance and carbon cycling, underscoring the need for field campaigns and process-rich models to forecast sink-source transitions (Teufel et al., 2019) and to improve Earth system simulations (Schädel et al., 2024; Seneviratne et al., 2010). The magnitude and timing of permafrost carbon release remain highly uncertain (M. C. Jones et al., 2023). Current models largely assume gradual thaw, ignoring abrupt events like collapse or wildfire that rapidly expose deep carbon (Chen et al., 2021;

Natali et al., 2021). Overshooting temperature targets can double or quadruple emissions, yet most Earth system models underestimate these feedbacks (Bui et al., 2020; Walvoord & Kurylyk, 2016). Explicit inclusion of abrupt thaw, supported by field data and remote sensing, is essential to improve predictions and inform climate policy.

6.4. Groundwater and Deep Processes

Most research and monitoring target the active layer and near-surface permafrost, yet thinning permafrost activates deeper groundwater systems with hydrological, biogeochemical, and ecological implications. Despite groundwater being identified as a catalyst for change in the Arctic (T. McKenzie et al., 2021), there is a paucity of direct groundwater observations in permafrost settings. Hydrogeological surveys and deep borehole networks logging temperature and aquifer pressures are needed to clarify permafrost-groundwater coupling and validate numerical models. Sparse observations mean large-scale models oversimplify dynamics, motivating multi-dimensional schemes that simulate groundwater flow in thawing permafrost (Devoie et al., 2019). A key gap is linking LSMs and surface hydrologic models with cryo-hydrogeologic models at watershed or regional scales in computationally efficient ways (Dai et al., 2019; Painter et al., 2023). Improved modeling tools need to be combined with integrated groundwater-surface water monitoring to resolve the complexities of evolving subsurface hydrologic connectivity as permafrost thaws. Beyond understanding the effects of permafrost on the physical hydrogeologic system, there remains an urgent need to resolve issues related to solute transport in frozen soils and associated cryo-hydrogeologic feedbacks. More research is needed in the area to support groundwater resource development and protection (Somers & McKenzie, 2020).

6.5. Climate Change and Water Resources Implications

Climate warming brings extremes, including rain-on-snow, sudden thaws, and heavy-snow years, which reshape frozen-soil processes. For example, mid-winter melt builds soil-ice layers that alter hydrology and the spring freshet. Rapid warming advances snowmelt and shrinks snowpack, altering seasonal water resources (Pulliainen et al., 2017). Recent studies show that warming-driven shifts in runoff seasonality already affect Arctic community water supplies and emphasize adaptation needs (Koch et al., 2024). Thaw-subsidence expands wetlands and shifts streamflow and storage (Korosi et al., 2017). While baseflow is increasing in many Arctic rivers due to permafrost thaw (S. G. Evans et al., 2020), the long-term cumulative effects of climate change (i.e., altered precipitation patterns, increasing wildfire) on streamflow are poorly understood. Complex recharge-evaporation interactions require models coupling cryo-hydrogeology with climate projections (Kurylyk et al., 2014). Research priorities include testing whether anomalous warming events trigger irreversible talik development, quantifying wildfire-driven permafrost degradation, and evaluating groundwater dynamics in thaw-activated aquifers (T. McKenzie et al., 2021). Active-layer thickening may buffer streamflow variability, but validation is limited (Kurylyk et al., 2014; Walvoord & Kurylyk, 2016). Retreating glaciers briefly add freshwater but raise sea levels and erode coasts, underscoring needs for long-term monitoring, advanced models, and better understanding of solutes, nutrients, and hydro-ecological feedbacks.

6.6. Emerging Technologies

Embracing emerging technologies is critical for advancing frozen soil hydrology. AI and ML are increasingly recognized as transformative tools, capable of extracting insights from the rapidly expanding volume of cold-region environmental data. For example, AI can systematically analyze multi-decadal satellite imagery to detect and quantify thermokarst lake dynamics or the timing of FT transitions (Hughes-Allen et al., 2023), tasks that would be prohibitively labor-intensive using traditional methods. ML techniques also offer value as emulators of computationally intensive model components. A trained neural network, for instance, could approximate the behavior of a high-resolution permafrost model, enabling its integration into global simulations at far lower computational cost. Early studies already demonstrate AI's potential in related domains. For example, Baghbani et al. (2022) reviewed AI applications in geotechnical engineering, including permafrost stability. Looking ahead, data-driven models could fill observational gaps by transferring knowledge from well-instrumented sites to unmonitored regions, while AI-based optimization can streamline parameter calibration by assimilating diverse inputs (e.g., soil, snow, vegetation, climate) more efficiently than traditional brute-force methods. Coupling AI with physics-based models offers a powerful path toward next-generation Earth system predictions.

6.7. Interdisciplinary Integration

Future research in cold regions should integrate social and engineering dimensions, advancing socio-hydrological studies that combine physical science, risk assessment, and adaptation. Human activities accelerate permafrost thaw, intensify emissions and ecosystem degradation, and disrupt water regulation, biodiversity, and carbon storage (J. P. Liu et al., 2020; Kreyling et al., 2021). Practical questions for infrastructure and resource development demand cross-sector collaboration. For example, how northern water supplies should adapt if winter flows rise with thaw events (Hjort et al., 2018). Integrated frameworks are emerging, where modelers and permafrost scientists embed FT processes and carbon feedback in Earth-system models (Hugelius et al., 2020; Y. Wang et al., 2014), while ecohydrology collaborations probe vegetation-microbe shifts in hydrologic cycles (Bosson et al., 2023). Field studies of roots, phenology, and groundwater interactions will inform models and anticipate shifts from carbon sinks to sources (Teufel et al., 2019). Recent reviews emphasize the importance of indigenous knowledge in Arctic hydrology, highlighting that co-production of knowledge generally improves both scientific models and community adaptation strategies (McCarty et al., 2021). Effective adaptation requires engineers, social scientists, policymakers, and indigenous communities to work together.

7. Conclusion and Synthesis

This review synthesizes recent advances and enduring challenges in frozen-soil hydrology. Frozen-soil processes fundamentally reshape cold-region water cycles and often exhibit threshold behaviors and feedbacks ongoing climate warming is already perturbing these dynamics with observable impacts on hydrology, ecosystems, and infrastructure. Despite progress in parameterizing FT cycles, thermal conductivity, and hydraulic properties, major uncertainties persist in representing non-conductive heat transfer and soil-water movement across flow regimes, and most models still under-represent salinity, organic matter, vegetation type, and root dynamics. Modeling and observational capacities have improved, yet key gaps remain in data coverage, scaling, and process understanding. Competing hypotheses, such as the magnitude of permafrost-carbon feedback and whether vegetation change stabilizes or destabilizes permafrost, require rigorous testing. Bridging micro-scale processes (e.g., cryosuction, macropore flow, talik formation) with watershed and Earth-system models is urgent. Priorities include multi-scale modeling frameworks that integrate detailed field studies with large-scale representations, comprehensive databases of permafrost properties, and enhanced monitoring networks (geophysics, remote sensing, community observations). Addressing these gaps will demand sustained, interdisciplinary, international collaboration over the coming decade to reduce uncertainty and inform adaptive management in cold regions.

Abbreviations

AHFO: Active heated fiber optics

ALT: Active layer thickness

CLM: Community Land Model

DPHP: Dual-probe heat-pulse

DTS: Distributed temperature sensing

EMI: Electromagnetic induction

ERT: Electrical resistivity tomography

FDR: Frequency domain reflectometry

FT: Freezing and thawing

FSM: Frozen soil model

GHG: Greenhouse gases

GPR: Ground-penetrating radar

QTP: Qinghai-Tibet Plateau

LSM: Land surface model

NMR: Nuclear magnetic resonance

Pe: Péclet number

SFCC: Soil freezing characteristic curve

SFG: Seasonally frozen ground

SWCC: Soil water characteristic curve

TDEM: Time-Domain Electromagnetics

TDR: Time-domain reflectometry

UAVs: Unmanned aerial vehicles

WD: Wetting-drying

WTD: Water table depth

Conflict of Interest

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

Data Availability Statement

The authors declare that no new data were used in this manuscript.

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References

Aas, K. S., Martin, L., Nitzbon, J., Langer, M., Boike, J., Lee, H., et al. (2019). Thaw processes in ice-rich permafrost landscapes represented with laterally coupled tiles in a land surface model. *The Cryosphere*, *13*(2), 591–609. https://doi.org/10.5194/tc-13-591-2019

Abu-Hamdeh, N. H., & Reeder, R. C. (2000). Soil thermal conductivity: Effects of density, moisture, salt concentration, and organic matter. *Soil Science Society of America Journal*, *64*(4), 1285–1290. https://doi.org/10.2136/sssaj2000.6441285x

Amankwah, S. K., Ireson, A. M., Maulé, C., Brannen, R., & Mathias, S. A. (2021). A model for the soil freezing characteristic curve that represents the dominant role of salt exclusion. *Water Resources Research*, *57*(8), e2021WR030070. https://doi.org/10.1029/2021WR030070

Appels, W. M., Coles, A. E., & McDonnell, J. J. (2018). Infiltration into frozen soil: From core-scale dynamics to hillslope-scale connectivity. *Hydrological Processes*, *32*(1), 66–79. https://doi.org/10.1002/hyp.11399

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: Model development 1. *JAWRA Journal of the American Water Resources Association*, *34*(1), 73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x

Baghbani, A., Choudhury, T., Costa, S., & Reiner, J. (2022). Application of artificial intelligence in geotechnical engineering: A state-of-the-art review. *Earth-Science Reviews*, *228*, 103991. https://doi.org/10.1108/EC-10-2020-0576

Bao, H., Koike, T., Yang, K., Wang, L., Shrestha, M., & Lawford, P. (2016). Development of an enthalpy based frozen soil model and its validation in a cold region in China. *Journal of Geophysical Research-Atmospheres*, *121*(10), 5259–5280. https://doi.org/10.1002/2015JD024451

Barker, A. J., Sullivan, T. D., Baxter, W. B., Barbato, R. A., Gallaher, S., Patton, G. E., et al. (2023). Iron oxidation-reduction processes in warming permafrost soils and surface waters expose a seasonally rusting Arctic watershed. *ACS Earth and Space Chemistry*, *7*(8), 1479–1495. https://doi.org/10.1021/acsearthspacechem.2c00367

Bayard, D., Stahli, M., Parriaux, A., & Fluhler, H. (2005). The influence of seasonally frozen soil on the snowmelt runoff at two Alpine sites in southern Switzerland. *Journal of Hydrology*, *309*(1–4), 66–84. https://doi.org/10.1016/j.jhydrol.2004.11.012

Bense, V. F., Ferguson, G., & Kooi, H. (2009). Evolution of shallow groundwater flow systems in areas of degrading permafrost. *Geophysical Research Letters*, *36*(22), L22401. https://doi.org/10.1029/2009GL039225

Bi, J., Wu, Z., Lu, Y., Wen, H., Zhang, Y., Shen, Y., et al. (2023). Study on soil freezing characteristic curve during a freeze–thaw process. *Frontiers in Earth Science*, *10*, 1007342. https://doi.org/10.3389/feart.2022.1007342

Biemans, H., Siderius, C., Lutz, A. F., Nepal, S., Ahmad, B., Hassan, T., et al. (2019). Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. *Nature Sustainability*, *2*(7), 594–601. https://doi.org/10.1038/s41893-019-0305-3

Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., et al. (2019). Permafrost is warming at a global scale. *Nature Communications*, *10*(1), 264. https://doi.org/10.1038/s41467-018-08240-4

Bittelli, M., Flury, M., & Campbell, G. S. (2003). A thermodielectric analyzer to measure the freezing and moisture characteristic of porous media. *Water Resources Research*, *39*(2), 1041. https://doi.org/10.1029/2001WR000930

Bittelli, M., Flury, M., & Roth, K. (2004). Use of dielectric spectroscopy to estimate ice content in frozen porous media. *Water Resources Research*, *40*(4), W04212. https://doi.org/10.1029/2003WR002343

Bloom, A. A., Bowman, K. W., Lee, M., Turner, A. J., Schroeder, R., Worden, J. R., et al. (2017). A global wetland methane emissions and uncertainty dataset for atmospheric chemical transport models (WetCHARTs version 1.0). *Geoscientific Model Development*, *10*(6), 2141–2156. https://doi.org/10.5194/gmd-10-2141-2017

Bonacina, C., Comini, G., Fasano, A., & Primicerio, M. (1973). Numerical solution of phase-change problems. *International Journal of Heat and Mass Transfer*, *16*(10), 1825–1832. https://doi.org/10.1016/0017-9310(73)90202-0

Bosson, J. B., Huss, M., Cauvy-Fraunié, S., Clément, J. C., Costes, G., Fischer, M., et al. (2023). Future emergence of new ecosystems caused by glacial retreat. *Nature*, *620*(7974), 562–569. https://doi.org/10.1038/s41586-023-06302-2

Bring, A., Fedorova, I., Dibike, Y., Hinzman, L., Mård, J., Mernild, S. H., et al. (2016). Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. *Journal of Geophysical Research: Biogeosciences*, *121*(3), 621–649. https://doi.org/10.1002/2015JG003131

Bui, M. T., Lu, J., & Nie, L. (2020). A review of hydrological models applied in the permafrost dominated Arctic region. *Geosciences*, *10*(10), 401. https://doi.org/10.3390/geosciences10100401

Burke, E. J., Zhang, Y., & Krinner, G. (2020). Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change. *The Cryosphere*, *14*(9), 3155–3174. https://doi.org/10.5194/tc-14-3155-2020

Cao, W., Sheng, Y., Wu, J. C., Chou, Y. L., Peng, E. X., & Leonid, G. (2021). Soil hydrological process and migration mode influenced by the FT process in the activity layer of permafrost regions in Qinghai-Tibet Plateau. *Cold Regions Science and Technology*, *184*, 14. https://doi.org/10.1016/j.coldregions.2021.103236

Carpino, O., Haynes, K., Connon, R., Craig, J., Devoie, E., & Quinton, W. (2021). Long-term climate-influenced land cover change in discontinuous permafrost peatland complexes. *Hydrology and Earth System Sciences*, *25*(6), 3301–3317. https://doi.org/10.5194/hess-25-3301-2021

Carpino, O., Wright, S., Guo, J., van der Sluijs, J., Connon, R., & Quinton, W. (2025). Detecting forest-wetland changes in northwestern Canada's discontinuous permafrost region using landsat trend analysis. *Ecohydrology*, *18*(1), e2759. https://doi.org/10.1002/eco.2759

Carpino, O. A., Berg, A. A., Quinton, W. L., & Adams, J. R. (2018). Climate change and permafrost thaw-induced boreal forest loss in northwestern Canada. *Environmental Research Letters*, *13*(8), 084018. https://doi.org/10.1088/1748-9326/aad74e

Chadburn, S. E., Burke, E. J., Cox, P. M., Friedlingstein, P., Hugelius, G., & Westermann, S. (2017). An observation-based constraint on permafrost loss as a function of global warming. *Nature Climate Change*, *7*(5), 340–344. https://doi.org/10.1038/nclimate3262

Chen, Y., Romps, D. M., Seeley, J. T., Veraverbeke, S., Riley, W. J., Mekonnen, Z. A., & Randerson, J. T. (2021). Future increases in Arctic lightning and fire risk for permafrost carbon. *Nature Climate Change*, *11*(5), 404–410. https://doi.org/10.1038/s41558-021-01011-y

Chuvilin, E. M., Bukhanov, B. A., Mukhametdinova, A. Z., Grechishcheva, E. S., Sokolova, N. S., Alekseev, A. G., & Istomin, V. A. (2022). Freezing point and unfrozen water contents of permafrost soils: Estimation by the water potential method. *Cold Regions Science and Technology*, *196*, 103488. https://doi.org/10.1016/j.coldregions.2022.103488

Clayton, L. K., Schaefer, K., Battaglia, M. J., Bourgeau-Chavez, L., Chen, J., Chen, R. H., et al. (2021). Active layer thickness as a function of soil water content. *Environmental Research Letters*, *16*(5), 055028. https://doi.org/10.1088/1748-9326/abfa4c

Congreves, K. A., Wagner-Riddle, B. C., Si, T. J., & Clough, T. (2018). Nitrous oxide emissions and biogeochemical responses to soil freeze–thaw and drying-wetting. *Soil Biology and Biochemistry*, *117*, 5–15. https://doi.org/10.1016/j.soilbio.2017.10.040

Connon, R. F., Chasmer, L., Haughton, E., Helbig, M., Hopkinson, C., Sonnentag, O., & Quinton, W. L. (2021). The implications of permafrost thaw and land cover change on snow water equivalent accumulation, melt and runoff in discontinuous permafrost peatlands. *Hydrological Processes*, *35*(9), e14363. https://doi.org/10.1002/hyp.14363

Connon, R. F., Devoie, É., Quinton, W. L., Veness, T., & Hayashi, M. (2018). The influence of shallow taliks on permafrost thaw and active layer dynamics in subarctic Canada. *Journal of Geophysical Research*, *123*(2), 281–297. https://doi.org/10.1002/2017JF004469

Creel, R., Guimond, J., Jones, B. M., Nielsen, D. M., Bristol, E., Tweedie, C. E., & Overduin, P. P. (2024). Permafrost thaw subsidence, sea-level rise, and erosion are transforming Alaska's Arctic coastal zone. *Proceedings of the National Academy of Sciences*, *121*(50), e2409411121. https://doi.org/10.1073/pnas.2409411121

Dai, Y., Shangguan, W., Wei, N., Xin, Q., Yuan, H., Zhang, S., et al. (2019). A review of the global soil property maps for Earth system models. *Soils*, *5*(2), 137–158. https://doi.org/10.5194/soil-5-137-2019

Del Grosso, S. J., Ogle, S. M., Nevison, C., Gurung, R., Parton, W. J., Wagner-Riddle, C., et al. (2022). A gap in nitrous oxide emission reporting complicates long-term climate mitigation. *Proceedings of the National Academy of Sciences*, *119*(31), e2200354119. https://doi.org/10.1073/pnas.2200354119

Denef, K., Six, J., Paustian, K., & Merchkx, R. (2001). Importance of macroaggregate dynamics in controlling soil carbon stabilization: Short-term effects of physical disturbance induced by dry-wet cycles. *Soil Biology and Biochemistry*, *33*(15), 2145–2153. https://doi.org/10.1016/S0038-0717(01)00153-5

Devoie, É. G., Connon, R. F., Beddoe, R., Goordial, J., Quinton, W. L., & Craig, J. R. (2023). Disconnected active layers and unfrozen permafrost: A discussion of permafrost-related terms and definitions. *Science of the Total Environment*, *912*, 169017. https://doi.org/10.1016/j.scitotenv.2023.169017

Devoie, E. G., Craig, J. R., Connon, R. F., & Quinton, W. L. (2019). Taliks: A tipping point in discontinuous permafrost degradation in peatlands. *Water Resources Research*, *55*(11), 9838–9857. https://doi.org/10.1029/2018WR024488

Devoie, E. G., Craig, J. R., Dominico, M., Carpino, O., Connon, R. F., Rudy, A. C. A., & Quinton, W. L. (2021). Mechanisms of discontinuous permafrost thaw in peatlands. *Journal of Geophysical Research-Earth Surface*, *126*(11), e2021JF006204. https://doi.org/10.1029/2021JF006204

Devoie, E. G., Gruber, S., & McKenzie, J. M. (2022). A repository of measured soil freezing characteristic curves: 1921 to 2021. *Earth System Science Data*, *14*(7), 3365–3377. https://doi.org/10.5194/essd-14-3365-2022

Diak, M., Böttcher, M. E., Ehlert von Ahn, C. M., Hong, W. L., Kędra, M., Kotwicki, L., et al. (2023). Permafrost and groundwater interaction: Current state and future perspective. *Frontiers in Earth Science*, *11*, 1254309. https://doi.org/10.3389/feart.2023.1254309

Domine, F., Fourteau, K., Picard, G., Lackner, G., Sarrazin, D., & Poirier, M. (2022). Permafrost cooled in winter by thermal bridging through snow-covered shrub branches. *Nature Geoscience*, *15*(7), 554–560. https://doi.org/10.1038/s41561-022-00979-2

Dong, Y., McCartney, J., & Lu, N. (2015). Critical review of thermal conductivity models for unsaturated soils. *Geotechnical & Geological Engineering*, *33*(2), 207–221. https://doi.org/10.1007/s10706-015-9843-2

Du, R., Peng, X., Frauenfeld, O. W., Sun, W., Liang, B., Chen, C., et al. (2022). The role of peat on permafrost thaw based on field observations. *Catena*, *208*, 105772. https://doi.org/10.1016/j.catena.2021.105772

Duan, Q., Ajami, N. K., Gao, X., & Sorooshian, S. (2007). Multi-model ensemble hydrologic prediction using Bayesian model averaging. *Advances in Water Resources*, *30*(5), 1371–1386. https://doi.org/10.1016/j.advwatres.2006.11.014

Endrizzi, S., Gruber, S., Dall'Amico, M., & Rigon, R. (2014). GEOtop 2. 0: Simulating the combined energy and water balance at and below the land surface accounting for soil freezing, snow cover and terrain effects. *Geoscientific Model Development*, *7*(6), 2831–2857. https://doi.org/10.5194/gmd-7-2831-2014

Evans, C. D., Peacock, M., Baird, A. J., Artz, R. R. E., Burden, A., Callaghan, N., et al. (2021). Overriding water table control on managed peatland greenhouse gas emissions. *Nature*, *593*(7860), 548–552. https://doi.org/10.1038/s41586-021-03523-1

Evans, S. G., & Ge, S. (2017). Contrasting hydrogeologic responses to warming in permafrost and seasonally frozen ground hillslopes. *Geophysical Research Letters*, *44*(4), 1803–1813. https://doi.org/10.1002/2016GL072009

Evans, S. G., Yokeley, B., Stephens, C., & Brewer, B. (2020). Potential mechanistic causes of increased baseflow across northern Eurasia catchments underlain by permaf-rost. *Hydrological Processes*, *34*(11), 2676–2690. https://doi.org/10.1002/hyp.13759

Fahnestock, M. F., Bryce, J. G., McCalley, C. K., Montesdeoca, M., Bai, S., Li, Y., & Varner, R. K. (2019). Mercury reallocation in thawing subarctic peatlands. *Geochemical Perspectives Letters*, *11*, 33–38. https://doi.org/10.7185/geochemlet.1922cor

Farouki, O. (1986). Thermal properties of soil. In *Series on rock and soil mechanic* (Vol. 11).

Farquharson, L. M., Romanovsky, V. E., Cable, W. L., Walker, D. A., Kokelj, S. V., & Nicolsky, D. (2019). Climate change drives widespread and rapid thermokarst development in very cold permafrost in the Canadian high Arctic. *Geophysical Research Letters*, *46*(12), 6681–6689. https://doi.org/10.1029/2019GL082187

Farquharson, L. M., Romanovsky, V. E., Kholodov, A., & Nicolsky, D. (2022). Sub-aerial talik formation observed across the discontinuous permafrost zone of Alaska. *Nature Geoscience*, *15*(6), 475–481. https://doi.org/10.1038/s41561-022-00952-z

Feng, D., Gleason, C. J., Lin, P., Yang, X., Pan, M., & Ishitsuka, Y. (2021). Recent changes to Arctic river discharge. *Nature Communications*, *12*(1), 6917. https://doi.org/10.1038/s41467-021-27228-1

Figura, S., Livingstone, D. M., Hoehn, E., & Kipfer, R. (2011). Regime shift in groundwater temperature triggered by Arctic oscillation. *Geophysical Research Letters*, *38*(23), L23401. https://doi.org/10.1029/2011GL049749

Flerchinger, G. N., & Saxton, K. E. (1989). Simultaneous heat and water (SHAW) model of a freezing snow–soil–plant system. *Transactions of the ASAE*, *32*(2), 565–571. https://doi.org/10.13031/2013.31040

Flores, J. A., Gleason, C. J., Brown, C., Vergopolan, N., Lummus, M. M., Stearns, L. A., et al. (2025). Accelerating river discharge in High Mountain Asia. *AGU Advances*, *6*(4), e2024AV001586. https://doi.org/10.1029/2024AV001586

Frampton, A., & Destouni, G. (2015). Impact of degrading permafrost on subsurface solute transport pathways and travel times. *Water Resources Research*, *51*(9), 7680–7701. https://doi.org/10.1002/2014WR016689

Frey, K. E., & McClelland, J. W. (2009). Impacts of permafrost degradation on arctic river biogeochemistry. *Hydrological Processes: International Journal*, *23*(1), 169–182. https://doi.org/10.1002/hyp.7196

Fu, Q., Hou, R., Li, T., Jiang, R., Yan, P., Ma, Z., & Zhou, Z. (2018). Effects of soil water and heat relationship under various snow cover during freeze–thaw periods in Songnen Plain, China. *Scientific Reports*, *8*(1), 1325. https://doi.org/10.1038/s41598-018-19467-y

Gao, B., Yang, D., Qin, Y., Wang, Y., Li, H., Zhang, Y., & Zhang, T. (2018). Change in frozen soils and its effect on regional hydrology, upper Heihe basin, northeastern Qinghai–Tibetan Plateau. *The Cryosphere*, *12*(2), 657–673. https://doi.org/10.5194/tc-12-657-2018

Gedney, N., Cox, P. M., & Huntingford, C. (2004). Climate feedback from wetland methane emissions. *Geophysical Research Letters*, *31*(20), L21202. https://doi.org/10.1029/2004GL020919

Gelfan, A., Gustafsson, D., Motovilov, Y., Arheimer, B., Kalugin, A., Krylenko, I., & Lavrenov, A. (2017). Climate change impact on the water regime of two great Arctic rivers: Modeling and uncertainty issues. *Climatic Change*, *141*(3), 499–515. https://doi.org/10.1007/s10584-016-1710-5

Gelfan, A., Panin, A., Kalugin, A., Morozova, P., Semenov, V., Sidorchuk, A., et al. (2024). Hydroclimatic processes as the primary drivers of the Early Khvalynian transgression of the Caspian Sea: New developments. *Hydrology and Earth System Sciences*, *28*(1), 241–259. https://doi.org/10.5194/hess-28-241-2024

Gelfan, A. N. (2010). Extreme snowmelt floods: Frequency assessment and analysis of genesis on the basis of the dynamic-stochastic approach. *Journal of Hydrology*, *388*(1–2), 85–99. https://doi.org/10.1016/j.jhydrol.2010.04.031

Geyman, E. C., Douglas, M. M., Avouac, J. P., & Lamb, M. P. (2024). Permafrost slows Arctic riverbank erosion. *Nature*, *634*(7939), 359–365. https://doi.org/10.1038/s41586-024-07978-w

Gordon, B. L., Brooks, P. D., Krogh, S. A., Boisrame, G. F., Carroll, R. W., McNamara, J. P., & Harpold, A. A. (2022). Why does snow melt-driven streamflow response to warming vary? A data-driven review and predictive framework. *Environmental Research Letters*, *17*(5), 053004. https://doi.org/10.1088/1748-9326/ac64b4

Granger, R. J., Gray, D. M., & Dyck, G. E. (1984). Snowmelt infiltration to frozen prairie soils. *Canadian Journal of Earth Sciences*, *21*(6), 669–677. https://doi.org/10.1139/E84-073

Gray, D. M., Toth, B., Zhao, L., Pomeroy, J. W., & Granger, R. J. (2001). Estimating areal snowmelt infiltration into frozen soils. *Hydrological Processes*, *15*(16), 3095–3111. https://doi.org/10.1002/hyp.320

Grenier, C., Anbergen, H., Bense, V., Chanzy, Q., Coon, E., Collier, N., et al. (2018). Groundwater flow and heat transport for systems undergoing freeze-thaw: Intercomparison of numerical simulators for 2D test cases. *Advances in Water Resources*, *114*, 196–218. https://doi.org/10.1016/j.advwatres.2018.02.001

Guo, D., Wang, H., Romanovsky, V. E., Haywood, A. M., Pepin, N., Salzmann, U., et al. (2023). Highly restricted n-ear-surface permafrost extent during the mid-Pliocene warm period. *Proceedings of the National Academy of Sciences*, *120*(36), e2301954120. https://doi.org/10.1073/pnas.2301954120

Guo, K., & Liu, X. (2021). Reclamation effect of freezing saline water irrigation on heavy saline-alkali soil in the Hetao Irrigation District of North China. *Catena*, *204*, 105420. https://doi.org/10.1016/j.catena.2021.105420

Gupta, A., Reverdy, A., Cohard, J. M., Hector, B., Descloitres, M., Vandervaere, J. P., et al. (2023). Impact of distributed meteorological forcing on simulated snow cover and hydrological fluxes over a mid-elevation alpine micro-scale catchment. *Hydrology and Earth System Sciences*, *27*(1), 191–212. https://doi.org/10.5194/hess-27-191-2023

Guymon, G. L., Hromadka, T. V., II, & Berg, R. L. (1980). A one dimensional frost heave model based upon simulation of simultaneous heat and water flux. *Cold Regions Science and Technology*, *3*(2–3), 253–262. https://doi.org/10.1016/0165-232X(80)90032-4

Hansson, K., Šimůnek, J., Mizoguchi, M., Lundin, L. C., & Van Genuchten, M. T. (2004). Water flow and heat transport in frozen soil: Numerical solution and FT applications. *Vadose Zone Journal*, *3*, 693–704. https://doi.org/10.2113/3.2.693

Harden, J. W., Koven, C. D., Ping, C. L., Hugelius, G., David McGuire, A., Camill, P., et al. (2012). Field information links permafrost carbon to physical vulnerabilities of thawing. *Geophysical Research Letters*, *39*(15), L15704. https://doi.org/10.1029/2012GL051958

Harlan, R. L. (1973). Analysis of coupled heat-fluid transport in partially frozen soil. *Water Resource Research*, *9*(5), 1314–1323. https://doi.org/10.1029/WR009i005p01314

Harris, C., Arenson, L. U., Christiansen, H. H., Etzelmüller, B., Frauenfelder, R., Gruber, S., et al. (2009). Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and geotechnical responses. *Earth-Science Reviews*, *92*(3–4), 117–171. https://doi.org/10.1016/j.earscirev.2008.12.002

Hayashi, M. (2013). The cold vadose zone: Hydrological and ecological significance of frozen-soil processes. *Vadose Zone Journal*, *12*(4), 1–8. https://doi.org/10.2136/vzj2013.03.0064

Haynes, K. M., Connon, R. F., & Quinton, W. L. (2018). Permafrost thaw induced drying of wetlands at Scotty Creek, NWT, Canada. *Environmental Research Letters*, *13*(11), 114001. https://doi.org/10.1088/1748-9326/aae46c

He, H., Dyck, M. F., Si, B. C., Zhang, T., Lv, J., & Wang, J. (2015). Soil freeze–thaw characteristics and snowmelt infiltration in Cryalfs of Alberta, Canada. *Geoderma Regional*, *5*, 198–208. https://doi.org/10.1016/j.geodrs.2015.08.001

He, H., Dyck, M. F., Wang, J., & Lv, J. (2015). Evaluation of TDR method for quantifying ice melting caused by heat pulse method for better estimating thermal properties of frozen soils. *Soil Science Society of America Journal*, *79*(5), 1275–1288. https://doi.org/10.2136/sssaj2014.12.0499

He, Z., Shook, K., Spence, C., Pomeroy, J. W., & Whitfield, C. (2023). Modeling the regional sensitivity of snowmelt, soil moisture, and streamflow generation to climate over the Canadian Prairies using a basin classification approach. *Hydrology and Earth System Sciences*, *27*(19), 3525–3546. https://doi.org/10.5194/hess-27-3525-2023

Heijmans, M. M., Magnússon, R. Í., Lara, M. J., Frost, G. V., Myers-Smith, I. H., van Huissteden, J., et al. (2022). Tundra vegetation change and impacts on permafrost. *Nature Reviews Earth & Environment*, *3*(1), 68–84. https://doi.org/10.1038/s43017-021-00233-0

Helbig, M., Waddington, J. M., Alekseychik, P., Amiro, B. D., Aurela, M., Barr, A. G., et al. (2020). Increasing contribution of peatlands to boreal evapotranspiration in a warming climate. *Nature Climate Change*, *10*(6), 555–560. https://doi.org/10.1038/s41558-020-0763-7

Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin, F. S., Dyurgerov, M. B., Fastie, C. L., et al. (2005). Evidence and implications of recent climate change in northern Alaska and other arctic regions. *Climatic Change*, *72*(3), 251–298. https://doi.org/10.1007/s10584-005-5352-2

Hjort, J., Karjalainen, O., Aalto, J., Westermann, S., Romanovsky, V. E., Nelson, F. E., et al. (2018). Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature Communications*, *9*(1), 5147. https://doi.org/10.1038/s41467-018-07557-4

Hjort, J., Streletskiy, D., Doré, G., Wu, Q., Bjella, K., & Luoto, M. (2022). Impacts of permafrost degradation on infrastructure. *Nature Reviews Earth & Environment*, *3*(1), 24–38. https://doi.org/10.1038/s43017-021-00247-8

Hodgkins, S. B., Tfaily, M. M., McCalley, C. K., Logan, T. A., Crill, P. M., Saleska, S. R., et al. (2014). Changes in peat chemistry associated with permafrost thaw increase greenhouse gas production. *Proceedings of the National Academy of Sciences*, *11*(16), 5819–5824. https://doi.org/10.1073/pnas.1314641111

Hu, G., Zhao, L., Li, R., Park, H., Wu, X., Su, Y., et al. (2023). Water and heat coupling processes and its simulation in frozen soils: Current status and future research directions. *Catena*, *222*, 106844. https://doi.org/10.1016/j.catena.2022.106844

Hu, G., Zhao, L., Wu, X., Li, R., Wu, T., Xie, C., et al. (2016). New fourier-series-based analytical solution to the conduction-convection equation to calculate soil temperature, determine soil thermal properties, or estimate water flux. *International Journal of Heat and Mass Transfer*, *95*, 815–823. https://doi.org/10.1016/j.ijheatmasstransfer.2015.11.078

Hu, G., Zhao, L., Zhu, X., Wu, X., Wu, T., Li, R., et al. (2020). Review of algorithms and parameterizations to determine unfrozen water content in frozen soil. *Geoderma*, *368*, 114277. https://doi.org/10.1016/j.geoderma.2020.114277

Hu, T., Wang, T., Chang, J., Liu, J., & Lu, Y. (2020). Code development and verification for the coupled process of water migration and heat transfer of frozen soil based on the finite volume method. *Rock and Soil Mechanics*, *5*, 1–9. https://doi.org/10.16285/j.rsm.2019.1263

Hu, W., Ma, W., Yang, Z. L., Ma, Y., Han, C., Xie, Z., et al. (2025). Mechanism analysis of simulation differences with two frozen soil permeability schemes in Noah-MP over the Tibetan Plateau. *Journal of Hydrology*, 133437. https://doi.org/10.1016/j.jhydrol.2025.1047759

Huang, X., & Rudolph, D. L. (2021). Coupled model for water, vapour, heat, stress and strain fields in variably saturated freezing soils. *Advances in Water Resources*, *154*, 103945. https://doi.org/10.1016/j.advwatres.2021.103945

Hubbard, S. S., Gangodagamage, C., Dafflon, B., Wainwright, H., Peterson, J., Gusmeroli, A., et al. (2013). Quantifying and relating land-surface and subsurface variability in permafrost environments using LiDAR and surface geophysical datasets. *Hydrogeology Journal*, *21*(1), 149–169. https://doi.org/10.1007/s10040-012-0939-y

Hugelius, G., Loisel, J., Chadburn, S., Jackson, R. B., Jones, M., MacDonald, G., et al. (2020). Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. *Proceedings of the National Academy of Sciences*, *117*(34), 20438–20446. https://doi.org/10.1073/pnas.1916387117

Hughes-Allen, L., Bouchard, F., Séjourné, A., Fougeron, G., & Léger, E. (2023). Automated identification of thermokarst lakes using machine learning in the ice-rich permafrost landscape of Central Yakutia (Eastern Siberia). *Remote Sensing*, *15*(5), 1226. https://doi.org/10.3390/rs15051226

Ireson, A. M., van der Kamp, G., Ferguson, G., Nachshon, U., & Wheater, H. S. (2013). Hydrogeological processes in seasonally frozen northern latitudes: Understanding, gaps and challenges. *Hydrogeology Journal*, *21*(1), 53–66. https://doi.org/10.1007/s10040-012-0916-5

Iwata, Y., Hayashi, M., & Hirota, T. (2008). Effects of snow cover on soil heat flux and freeze-thaw processes. *Journal of Agricultural Meteorology*, *64*(4), 301–309. https://doi.org/10.2480/agrmet.64.4.12

Iwata, Y., Hayashi, M., Suzuki, S., Hirota, T., & Hasegawa, S. (2010). Effects of snow cover on soil freezing, water movement, and snowmelt infiltration: A paired plot experiment. *Water Resources Research*, *46*(9), W09504. https://doi.org/10.1029/2009WR008070

Jame, Y. W., & Norum, D. I. (1980). Heat and mass transfer in a freezing unsaturated porous medium. *Water Resources Research*, *16*(4), 811–819. https://doi.org/10.1029/WR016i004p00811

Jammet, M., Dengel, S., Kettner, E., Parmentier, F. J. W., Wik, M., Crill, P., & Friborg, T. (2017). Year-round CH_4 and CO_2 flux dynamics in two contrasting freshwater ecosystems of the subarctic. *Biogeosciences*, *14*(22), 5189–5216. https://doi.org/10.5194/bg-14-5189-2017

Jansson, P. (2012). COUP model: Model use, calibration, and validation. *Transactions of the ASABE*, *55*(4), 1335–1344. https://doi.org/10.13031/2013.42245

Jansson, P., & Karlberg, L. (2004). COUP model–coupled heat and mass transfer model for soil-plant atmosphere system. In *Trita-LWR report, 3087*.

Jepsen, S. M., Walvoord, M. A., Voss, C. I., & Rover, J. (2016). Effect of permafrost thaw on the dynamics of lakes recharged by ice-jam floods: Case study of Yukon Flats, Alaska. *Hydrological Processes*, *30*(11), 1782–1795. https://doi.org/10.1002/hyp.10756

Jiang, H., Zheng, G., Yi, Y., Chen, D., Zhang, W., Yang, K., & Miller, C. E. (2020). Progress and challenges in studying regional permafrost in the Tibetan Plateau using satellite remote sensing and models. *Frontiers in Earth Science*, *8*, 560403. https://doi.org/10.3389/feart.2020.560403

Jiang, R., Bai, X., Wang, X., Hou, R., Liu, X., & Yang, H. (2024). Effects of freeze–thaw cycles and the prefreezing water content on the soil pore size distribution. *Water*, *16*(14), 2040. https://doi.org/10.3390/w16142040

Johnson, H., & Lundin, L. C. (1991). Surface runoff and soil water percolation as affected by snow and soil frost. *Journal of Hydrology*, *122*(1–4), 141–159. https://doi.org/10.1016/0022-1694(91)90177-J

Jones, D. B., Harrison, S., Anderson, K., & Betts, R. A. (2018). Mountain rock glaciers contain globally significant water stores. *Scientific Reports*, *8*(1), 2834. https://doi.org/10.1038/s41598-018-21244-w

Jones, M. C., Grosse, G., Treat, C., Turetsky, M., Anthony, K. W., & Brosius, L. (2023). Past permafrost dynamics can inform future permafrost carbon-climate feedbacks. *Communications Earth & Environment*, *4*(1), 272. https://doi.org/10.1038/s43247-023-00886-3

Kääb, A., & Røste, J. (2024). Rock glaciers across the United States predominantly accelerate coincident with rise in air temperatures. *Nature Communications*, *15*(1), 7581. https://doi.org/10.1038/s41467-024-52093-z
Kane, D. L., & Stein, J. (1983). Water movement into seasonally frozen soils. *Water Resources Research*, *19*(6), 1547–1557. https://doi.org/10.1029/WR019i006p01547
Kanno, Y., Vokoun, J. C., & Letcher, B. H. (2014). Paired stream-air temperature measurements reveal fine-scale thermal heterogeneity within headwater brook trout stream networks. *River Research and Applications*, *30*(6), 745–755. https://doi.org/10.1002/rra.2677
Kay, B. D., & Groenevelt, P. H. (1974). On the interaction of water and heat transport in frozen and unfrozen soils: I. Basic theory; the vapor phase. *Soil Science Society of America Journal*, *38*(3), 395–400. https://doi.org/10.2136/sssaj1974.03615995003800030011x
King, T. V., Neilson, B. T., Overbeck, L. D., & Kane, D. L. (2020). A distributed analysis of lateral inflows in an Alaskan Arctic watershed underlain by continuous permafrost. *Hydrological Processes*, *34*(3), 633–648. https://doi.org/10.1002/hyp.13611
Koch, J. C., Connolly, C. T., Baughman, C., Repasch, M., Best, H., & Hunt, A. (2024). The dominance and growth of shallow groundwater resources in continuous permafrost environments. *Proceedings of the National Academy of Sciences*, *121*(23), e2317873121. https://doi.org/10.1073/pnas.2317873121
Koirala, S., Yeh, P. J. F., Hirabayashi, Y., Kanae, S., & Oki, T. (2014). Global-scale land surface hydrologic modeling with the representation of water table dynamics. *Journal of Geophysical Research: Atmospheres*, *119*(1), 75–89. https://doi.org/10.1002/2013JD020398
Kojima, Y., Heitman, J. L., Flerchinger, G. N., & Horton, R. (2013). Numerical evaluation of a sensible heat balance method to determine rates of soil freezing and thawing. *Vadose Zone Journal*, *12*(1), 1–11. https://doi.org/10.2136/Vzj2012.0053
Kokelj, S. V., Tunnicliffe, J., Lacelle, D., Lantz, T. C., Chin, K. S., & Fraser, R. (2015). Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada. *Global and Planetary Change*, *135*, 207–268. https://doi.org/10.1016/j.gloplacha.2015.02.008
Koren, V., Schaake, J., Mitchell, K., Duan, Q. Y., Chen, F., & Baker, J. M. (1999). A parameterization of snowpack and frozen ground intended for NCEP weather and climate models. *Journal of Geophysical Research*, *104*(D16), 19569–19586. https://doi.org/10.1029/1999JD900232
Korosi, J., Thienpont, J., Pisaric, M., de Montigny, P., Perreault, J., McDonald, J., et al. (2017). Broad-scale lake expansion and flooding inundates essential wood bison habitat. *Nature Commuications*, *8*(1), 14510. https://doi.org/10.1038/ncomms14510
Kreyling, J., Tanneberger, F., Jansen, F., Van Der Linden, S., Aggenbach, C., Blüml, V., et al. (2021). Rewetting does not return drained fen peatlands to their old selves. *Nature Communications*, *12*(1), 5693. https://doi.org/10.1038/s41467-021-25619-y
Kuang, X., Liu, J., Scanlon, B. R., Jiao, J. J., Jasechko, S., Lancia, M., et al. (2024). The changing nature of groundwater in the global water cycle. *Science*, *383*(6686), eadf0630. https://doi.org/10.1126/science.adf0630
Kuchment, L. S., Gelfan, A. N., & Demidov, V. N. (2000). A distributed model of runoff generation in the permafrost regions. *Journal of Hydrology*, *240*(1–2), 1–2. https://doi.org/10.1016/S0022-1694(00)00318-8
Kudryavtsev, V. A. (1977). *Fundamentals of frost forecasting in geological engineering investigations (draft translation 606)* (p. 489). Cold Regions Research and Engineering Laboratory (CRREL).
Kurylyk, B. L., & Hayashi, M. (2016). Improved Stefan equation correction factors to accommodate sensible heat storage during soil freezing or thawing. *Permafrost and Periglacial Processes*, *27*(2), 189–203. https://doi.org/10.1002/ppp.1865
Kurylyk, B. L., MacQuarrie, K. T., & McKenzie, J. M. (2014). Climate change impacts on groundwater and soil temperatures in cold and temperate regions: Implications, mathematical theory, and emerging simulation tools. *Earth-Science Reviews*, *138*, 313–334. https://doi.org/10.1016/j.earscirev.2014.06.006
Kurylyk, B. L., & Watanabe, K. (2013). The mathematical representation of freezing and thawing processes in variably-saturated, non-deformable soils. *Advances in Water Resources*, *60*, 160–177. https://doi.org/10.1016/j.advwatres.2013.07.016
Lacelle, D., Fisher, D. A., Verret, M., & Pollard, W. (2022). Improved prediction of the vertical distribution of ground ice in Arctic-Antarctic permafrost sediments. *Communications Earth & Environment*, *3*(1), 31. https://doi.org/10.1038/s43247-022-00367-z
Lai, Y., Pei, W., Zhang, M., & Zhou, J. (2014). Study on theory model of hydro-thermal-mechanical interaction process in saturated freezing silty soil. *International Journal of Heat and Mass Transfer*, *78*, 805–819. https://doi.org/10.1016/j.ijheatmasstransfer.2014.07.035
Lan, C., Zhang, Y., Bohn, T. J., Zhao, L., Li, J., Liu, Q., & Zhou, B. (2015). Frozen soil degradation and its effects on surface hydrology in the northern Tibetan Plateau. *Journal of Geophysical Research-Atmospheres*, *120*(16), 8276–8298. https://doi.org/10.1002/2015JD023193
Langer, M., Von Deimling, T. S., Westermann, S., Rolph, R., Rutte, R., Antonova, S., et al. (2023). Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination. *Nature Communications*, *14*(1), 1721. https://doi.org/10.1038/s41467-023-37276-4
Lantz, T. C., & Turner, K. W. (2015). Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. *Journal of Geophysical Research: Biogeosciences*, *120*(3), 513–524. https://doi.org/10.1002/2014JG002744
Lawrence, D. M., & Slater, A. G. (2008). Incorporating organic soil into a global climate model. *Climate Dynamics*, *30*(2–3), 145–160. https://doi.org/10.1007/s00382-007-0278-1
Lemieux, J. M., Frampton, A., & Fortier, P. (2025). Recent advances (2018–2023) and research opportunities in the study of groundwater in cold regions. *Permafrost and Periglacial Processes*, *36*(1), 93–109. https://doi.org/10.1002/ppp.2255
Lewkowicz, A. G., & Way, R. G. (2019). Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment. *Nature Communications*, *10*(1), 1329. https://doi.org/10.1038/s41467-019-09314-7
Li, J., Wang, W., Ke, X., Li, J., Yu, Y., Gao, Z., & Niu, F. (2021). Impacts of groundwater flow on the evolution of a thermokarst lake in the permafrost–dominated region on the Qinghai–Tibet plateau. *Hydrological Processes*, *35*(12), e14443. https://doi.org/10.1002/hyp.14443
Li, J. B., Zhao, Y., Zhang, A. F., Song, B., & Hill, R. L. (2021). Effect of grazing exclusion on nitrous oxide emissions during freeze-thaw cycles in a typical steppe of Inner Mongolia. *Agriculture, Ecosystems & Environment*, *307*, 107217. https://doi.org/10.1016/j.agee.2020.107217
Li, K. Q., Yin, Z. Y., & Liu, Y. (2023). Influences of spatial variability of hydrothermal properties on the freezing process in artificial ground freezing technique. *Computers and Geotechnics*, *159*, 105448. https://doi.org/10.1016/j.compgeo.2023.105448
Li, Q., Xue, Y., & Liu, Y. (2021). Impact of frozen soil processes on soil thermal characteristics at seasonal to decadal scales over the Tibetan Plateau and North China. *Hydrology and Earth System Sciences*, *25*(4), 2089–2107. https://doi.org/10.5194/hess-25-2089-2021
Li, X., Cheng, G., Jin, H., Kang, E., Che, T., Jin, R., et al. (2021). Changes in the extent of seasonally frozen ground in the Northern Hemisphere. *Journal of Geophysical Research: Atmospheres*, *126*(3), e2020JD033573. https://doi.org/10.1029/2020JD033573
Liang, X., Lettenmaier, D. P., Wood, E. F., & Burges, S. J. (1994). A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research*, *99*(D7), 14415–14428. https://doi.org/10.1029/94JD00483
Lindström, G., Bishop, K., & Löfvenius, M. O. (2002). Soil frost and runoff at Svartberget, northern Sweden—Measurements and model analysis. *Hydrological Processes*, *16*(17), 3379–3392. https://doi.org/10.1002/hyp.1106
Liu, H., Price, J., Rezanezhad, F., & Lennartz, B. (2020). Centennial-scale shifts in hydrophysical properties of peat induced by drainage. *Water Resources Research*, *56*(10), e2020WR027538. https://doi.org/10.1029/2020WR027538

Liu, J., & Lobb, D. A. (2021). An overview of crop and crop residue management impacts on crop water use and runoff in the Canadian prairies. *Water*, *13*(20), 2929. https://doi.org/10.3390/w13202929

Liu, J. P., Yang, P., & Yang, Z. H. (2020). Electrical properties of frozen saline clay and their relationship with unfrozen water content. *Cold Regions Science and Technology*, *178*, 103127. https://doi.org/10.1016/j.coldregions.2020.103127

Liu, S., Huang, Q., Ren, D., Xu, X., Xiong, Y., & Huang, G. (2021). Soil evaporation and its impact on salt accumulation in different landscapes under freeze-thaw conditions in an arid seasonal frozen region. *Vadose Zone Journal*, *20*(2), e20098. https://doi.org/10.1002/vzj2.20098

Liu, Z., Chen, B., Wang, S., Wang, Q., Chen, J., Shi, W., et al. (2021). The impacts of vegetation on the soil surface freezing-thawing processes at permafrost southern edge simulated by an improved process-based ecosystem model. *Ecological Modelling*, *456*, 109663. https://doi.org/10.1016/j.ecolmodel.2021.109663

Lundin, L. C. (1990). Hydraulic properties in an operational model of frozen soil. *Journal of Hydrology*, *118*(1–4), 289–310. https://doi.org/10.1016/0022-1694(90)90264-X

McCarty, J. L., Aalto, J., Paunu, V. V., Arnold, S. R., Eckhardt, S., Klimont, Z., & Wilson, S. (2021). Reviews & syntheses: Arctic fire regimes and emissions in the 21st century. *Biogeosciences Discussions*, *2021*, 1–59. https://doi.org/10.5194/bg-18-5053-2021

McKenzie, J. M., Voss, C. I., & Siegel, D. I. (2007). Groundwater flow with energy transport and water-ice phase change: Numerical simulations, benchmarks, and application to freezing in peat bogs. *Advances in Water Resources*, *30*(4), 966–983. https://doi.org/10.1016/j.advwatres.2006.08.008

McKenzie, T., Dulai, H., & Fuleky, P. (2021). Traditional and novel time-series approaches reveal submarine groundwater discharge dynamics under baseline and extreme event conditions. *Scientific Reports*, *11*(1), 22570. https://doi.org/10.1038/s41598-021-01920-0

Michel, F. A., & van Everdingen, R. O. (2006). Changes in hydrogeologic regimes in permafrost regions due to climatic change. *Permafrost and Periglacial Processes*, *5*(3), 191–195. https://doi.org/10.1002/ppp.3430050308

Miner, K. R., Turetsky, M. R., Malina, E., Bartsch, A., Tamminen, J., McGuire, A. D., et al. (2022). Permafrost carbon emissions in a changing Arctic. *Nature Reviews Earth & Environment*, *3*(1), 55–67. https://doi.org/10.1038/s43017-021-00230-3

Ming, F., Chen, L., Li, D., & Du, C. (2020). Investigation into freezing point depression in soil caused by NaCl solution. *Water*, *12*(8), 2232. https://doi.org/10.3390/w12082232

Minsley, B. J., Abraham, J. D., Smith, B. D., Cannia, J. C., Voss, C. I., Jorgenson, M. T., et al. (2012). Airborne electromagnetic imaging of discontinuous permafrost. *Geophysical Research Letters*, *39*(2), 197. https://doi.org/10.1029/2011GL050079

Mohammed, A. A., Cey, E. E., Hayashi, M., & Callaghan, M. V. (2021). Simulating preferential flow and snowmelt partitioning in seasonally frozen hillslopes. *Hydrological Processes*, *35*(8), e14277. https://doi.org/10.1002/hyp.14277

Mohammed, A. A., Cey, E. E., Hayashi, M., Callaghan, M. V., Park, Y. J., Miller, K. L., & Frey, S. K. (2021). Dual-permeability modeling of preferential flow and snowmelt partitioning in frozen soils. *Vadose Zone Journal*, *20*(2), e20101. https://doi.org/10.1002/vzj2.2010

Mohammed, A. A., Kurylyk, B. L., Cey, E. E., & Hayashi, M. (2018). Snowmelt infiltration and macropore flow in frozen soils: Overview, knowledge gaps, and a conceptual framework. *Vadose Zone Journal*, *17*(1), 180084-15. https://doi.org/10.2136/vzj2018.04.0084

Motovilov, Y. G. (1977). Numerical modeling of the infiltration of water into frozen soils. *Soviet Meteorology and Hydrology*, *9*, 55–62.

Mwangi, S., Zeng, Y. J., Montzka, C., Yu, L. Y., & Su, Z. B. (2020). Assimilation of cosmic-ray neutron counts for the estimation of soil ice content on the Eastern Tibetan Plateau. *Journal of Geophysical Research-Atmospheres*, *125*(3), 1–23. https://doi.org/10.1029/2019jd031529

Nakata, Y., Hayamizu, M., Ishiyama, N., & Torita, H. (2021). Observation of diurnal ground surface changes due to freeze-thaw action by real-time kinematic unmanned aerial vehicle. *Remote Sensing*, *13*(11), 2167. https://doi.org/10.3390/rs13112167

Nan, Z., Li, S., Cheng, G., & Huang, P. (2012). Surface frost number model and its application to the Tibetan Plateau. *Journal of Glaciology and Geocryology*, *34*(1), 89–95. https://doi.org/10.7522/j.issn.1000-0240.2012.0012

Natali, S. M., Holdren, J. P., Rogers, B. M., Treharne, R., Duffy, P. B., Pomerance, R., & MacDonald, E. (2021). Permafrost carbon feedbacks threaten global climate goals. *Proceedings of the National Academy of Sciences*, *118*(21), e2100163118. https://doi.org/10.1073/pnas.2100163118

Nelson, F. E., & Outcalt, S. I. (1987). A computational method for prediction and regionalization of permafrost. *Arctic and Alpine Research*, *19*(3), 279–288. https://doi.org/10.1080/00040851.1987.12002602

Nicolsky, D., Romanovsky, V., Alexeev, V., & Lawrence, D. (2007). Improved modeling of permafrost dynamics in a GCM land-surface scheme. *Geophysical Research Letters*, *34*(8), L08501. https://doi.org/10.1029/2007GL029525

Nielsen-Englyst, P., Høyer, J. L., Kolbe, W. M., Dybkjær, G., Lavergne, T., Tonboe, R. T., et al. (2023). A combined sea and sea-ice surface temperature climate dataset of the Arctic, 1982–2021. *Remote Sensing of Environment*, *284*, 113331. https://doi.org/10.1016/j.rse.2022.113331

Nitzbon, J., Westermann, S., Langer, M., Martin, L. C., Strauss, J., Laboor, S., & Boike, J. (2020). Fast response of cold ice-rich permafrost in northeast Siberia to a warming climate. *Nature Communications*, *11*(1), 2201. https://doi.org/10.1038/s41467-020-15725-8

Nitze, I., Grosse, G., Jones, B., Romanovsky, V., & Boike, J. (2018). Remote sensing quantifies widespread abundance of permafrost region disturbances across the Arctic and Subarctic. *Nature Communications*, *9*(1), 5423. https://doi.org/10.1038/s41467-018-07663-3

Niu, G., & Yang, Z. (2006). Effects of frozen soil on snowmelt runoff and soil water storage at a continental scale. *Journal of Hydrometeorology*, *7*(5), 937–952. https://doi.org/10.1175/JHM538.1

Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., et al. (2019). Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km^2 scale. *Earth-Science Reviews*, *193*, 299–316. https://doi.org/10.1016/j.earscirev.2019.04.023

Ochsner, T. E., & Baker, J. M. (2008). In situ monitoring of soil thermal properties and heat flux during freezing and thawing. *Soil Science Society of America Journal*, *72*(4), 1025–1032. https://doi.org/10.2136/sssaj2007.0283

Oleson, K. W., Lawrence, D. M., Bonan, G. B., Fisher, R. A., Lawrence, P. J., & Muszala, S. P. (2013). Technical description of version 4.5 of the Community Land Model (CLM). In *Technical description of version 4.5 of the Community Land Model (CLM)(2013) NCAR/TN-503+ STR, 503*. https://doi.org/10.5065/D6RR1W7M

O'Neill, H. B., Smith, S. L., Burn, C. R., Duchesne, C., & Zhang, Y. (2023). Widespread permafrost degradation and thaw subsidence in northwest Canada. *Journal of Geophysical Research: Earth Surface*, *128*(8), e2023JF007262. https://doi.org/10.1029/2023JF007262

O'Neill, K., & Miller, R. D. (1985). Exploration of a rigid ice model of frost heave. *Water Resources Research*, *21*(3), 281–296. https://doi.org/10.1029/WR021i003p00281

Osterwalder, S., Bishop, K., Alewell, C., Fritsche, J., Laudon, H., Akerblom, S., & Nilsson, M. B. (2017). Mercury evasion from a boreal peatland shortens the timeline for recovery from legacy pollution. *Scientific Reports*, *7*(1), 16022. https://doi.org/10.1038/s41598-017-16141-7

Ozsoy, A., & Yildirim, R. (2016). Prevention of icing with ground source heat pipe: A theoretical analysis for Turkey's climatic conditions. *Cold Regions Science and Technology*, *125*, 65–71. https://doi.org/10.1016/j.coldregions.2016.02.003

Painter, S. L., Coon, E. T., Khattak, A. J., & Jastrow, J. D. (2023). Drying of tundra landscapes will limit subsidence-induced acceleration of permafrost thaw. *Proceedings of the National Academy of Sciences*, *120*(8), e2212171120. https://doi.org/10.1073/pnas.2212171120

Patzner, M. S., Mueller, C. W., Malusova, M., Baur, M., Nikeleit, V., Scholten, T., et al. (2020). Iron mineral dissolution releases iron and associated organic carbon during permafrost thaw. *Nature Communications*, *11*(1), 6329. https://doi.org/10.1038/s41467-020-20102-6

Paul, M. J., LeDuc, S. D., Lassiter, M. G., Moorhead, L. C., Noyes, P. D., & Leibowitz, S. G. (2022). Wildfire induces changes in receiving waters: A review with considerations for water quality management. *Water Resources Research*, *58*(9), e2021WR030699. https://doi.org/10.1029/2021WR030699

Peng, Z., Tian, F., Wu, J., Huang, J., Hu, H., & Darnault, C. J. G. (2016). A numerical model for water and heat transport in freezing soils with nonequilibrium ice-water interfaces. *Water Resources Research*, *52*(9), 7366–7381. https://doi.org/10.1002/2016WR019116

Piovano, T. I., Tetzlaff, D., Carey, S. K., Shatilla, N. J., Smith, A., & Soulsby, C. (2019). Spatially distributed tracer-aided runoff modelling and dynamics of storage and water ages in a permafrost-influenced catchment. *Hydrology and Earth System Sciences*, *23*(6), 2507–2523. https://doi.org/10.5194/hess-23-2507-2019

Pitman, A., Slater, A., Desborough, C., & Zhao, M. (1999). Uncertainty in the simulation of runoff due to the parameterization of frozen soil moisture using the Global Soil Wetness Project methodology. *Journal of Geophysical Research*, *104*(D14), 16879–16888. https://doi.org/10.1029/1999JD900261

Pomeroy, J. W., Gray, D. M., Brown, T., Hedstrom, N. R., Quinton, W. L., Granger, R. J., & Carey, S. K. (2007). The cold regions hydrological process representation and model: A platform for basing model structure on physical evidence. *Hydrological Processes*, *21*(19), 2650–2667. https://doi.org/10.1002/hyp.6787

Poutou, E., Krinner, G., Genthon, C., & de Noblet-Ducoudre, N. (2004). Role of soil freezing in future boreal climate change. *Climate Dynamics*, *23*(6), 621–639. https://doi.org/10.1007/s00382-004-0459-0

Prowse, T., Bonsal, B., Duguay, C., & Lacroix, M. (2007). River-ice break-up/freeze-up: A review of climatic drivers, historical trends, and future predictions. *Annals of Glaciology*, *46*, 443–451. https://doi.org/10.3189/172756407782871431

Pulliainen, J., Aurela, M., Laurila, T., Aalto, T., Takala, M., Salminen, M., et al. (2017). Early snowmelt significantly enhances boreal springtime carbon uptake. *Proceedings of the National Academy of Sciences*, *114*(42), 11081–11086. https://doi.org/10.1073/pnas.1707889114

Qin, Y., Bai, Y., Chen, G., Liang, Y., Li, X., Wen, B., et al. (2021). The effects of soil freeze–thaw processes on water and salt migrations in the western Songnen Plain, China. *Scientific Reports*, *11*(1), 3888. https://doi.org/10.1038/s41598-021-83294-x

Quinton, W. L., & Marsh, P. (1999). A conceptual framework for runoff generation in a permafrost environment. *Hydrological Processes*, *13*(14-15), 2563–2581. https://doi.org/10.1002/(SICI)1099-1085(199910)13:14/15<2563::AID-HYP942>3.0.CO;2-D

Ran, H., Fan, J., & Huang, J. (2019). Review of the coupling of water and heat in the freeze-thaw process and its model of frozen soil. *Pratacultural Science*, *36*(4), 991–999.

Ran, Y., Cheng, G., Dong, Y., Hjort, J., Lovecraft, A. L., Kang, S., et al. (2022). Permafrost degradation increases risk and large future costs of infrastructure on the Third Pole. *Communications Earth & Environment*, *3*(1), 238. https://doi.org/10.1038/s43247-022-00568-6

Rau, G. C., Anderson, M. S., McCallum, A. M., Roshan, H., & Acworth, R. I. (2014). Heat as a tracer to quantify water flow in near-surface sediments. *Earth-Science Reviews*, *129*, 40–58. https://doi.org/10.1016/j.earscirev.2013.10.015

Rautiainen, K., Parkkinen, T., Lemmetyinen, J., Schwank, M., Wiesmann, A., Ikonen, J., et al. (2016). SMOS prototype algorithm for detecting autumn soil freezing. *Remote Sensing of Environment*, *180*, 346–360. https://doi.org/10.1016/j.rse.2016.01.012

Rawlins, M. A., & Karmalkar, A. V. (2024). Regime shifts in Arctic terrestrial hydrology manifested from impacts of climate warming. *The Cryosphere*, *18*(3), 1033–1057. https://doi.org/10.5194/tc-18-1033-2024

Risk, N., Wagner-Riddle, C., Furon, A., Warland, J., & Blodau, C. (2014). Comparison of simultaneous soil profile N_2O concentration and surface N_2O flux measurements overwinter and at spring thaw in an agricultural soil. *Soil Science Society of America Journal*, *78*(1), 180–193. https://doi.org/10.2136/sssaj2013.06.0221

Rodenhizer, H., Natali, S. M., Mauritz, M., Taylor, M. A., Celis, G., Kadej, S., et al. (2023). Abrupt permafrost thaw drives spatially heterogeneous soil moisture and carbon dioxide fluxes in upland tundra. *Global Change Biology*, *29*(22), 6286–6302. https://doi.org/10.1111/gcb.16936

Rouabhi, A., Jahangir, E., & Tounsi, H. (2018). Modeling heat and mass transfer during ground freezing taking into account the salinity of the saturating fluid. *International Journal of Heat and Mass Transfer*, *120*, 523–533. https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.065

Sanchez-Rodriguez, I., Ireson, A., Brannen, R., & Brauner, H. (2025). Insights into freeze–thaw and infiltration in seasonally frozen soils from field observations. *Vadose Zone Journal*, *24*(1), e20396. https://doi.org/10.1002/vzj2.20396

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., et al. (2020). The global methane budget 2000–2017. *Earth System Science Data*, *12*(3), 1561–1623. https://doi.org/10.5194/essd-12-1561-2020

Schädel, C., Rogers, B. M., Lawrence, D. M., Koven, C. D., Brovkin, V., Burke, E. J., et al. (2024). Earth system models must include permafrost carbon processes. *Nature Climate Change*, *14*(2), 114–116. https://doi.org/10.1038/s41558-023-01909-9

Schuur, E. A., Abbott, B. W., Commane, R., Ernakovich, J., Euskirchen, E., Hugelius, G., et al. (2022). Permafrost and climate change: Carbon cycle feedbacks from the warming Arctic. *Annual Review of Environment and Resources*, *47*(1), 343–371. https://doi.org/10.1146/annurev-environ-012220-011847

Schuur, E. A., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., et al. (2015). Climate change and the permafrost carbon feedback. *Nature*, *520*(7546), 171–179. https://doi.org/10.1038/nature14338

Schuur, E. A. G., & Mack, M. C. (2018). Ecological response to permafrost thaw and consequences for local and global ecosystem services. *Annual Review of Ecology, Evolution, and Systematics*, *49*(1), 279–301. https://doi.org/10.1146/annurev-ecolsys-121415-032349

Semenova, O., Vinogradov, Y., Vinogradova, T., & Lebedeva, L. (2014). Simulation of soil profile heat dynamics and their integration into hydrologic modelling in a Permafrost Zone. *Permafrost and Periglacial Processes*, *25*(4), 257–269. https://doi.org/10.1002/ppp.1820

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., et al. (2010). Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews*, *99*(3–4), 125–161. https://doi.org/10.1016/j.earscirev.2010.02.004

Seok, B., Helmig, D., Williams, M., Liptzin, D., Chowanski, K., & Hueber, J. (2009). An automated system for continuous measurements of trace gas fluxes through snow: An evaluation of the gas diffusion method at a subalpine forest site, Niwot Ridge, Colorado. *Biogeochemistry*, *95*(1), 95–113. https://doi.org/10.1007/s10533-009-9302-3

Seyfried, M., Link, T., Marks, D., & Murdock, M. (2016). Soil temperature variability in complex terrain measured using fiber-optic distributed temperature sensing. *Vadose Zone Journal*, *15*(6), vzj2015-09-18. https://doi.org/10.2136/vzj2015.09.0128

Shi, R., Yang, H., & Yang, D. (2020). Spatiotemporal variations in frozen ground and their impacts on hydrological components in the source region of the Yangtze River. *Journal of Hydrology*, *590*, 125237. https://doi.org/10.1016/j.jhydrol.2020.125237

Shiklomanov, N. I., Streletskiy, D. A., Little, J. D., & Nelson, F. E. (2013). Isotropic thaw subsidence in undisturbed permafrost landscapes. *Geophysical Research Letters*, *40*(24), 6356–6361. https://doi.org/10.1002/2013gl058295

Singh, A. K., & Chaudhary, D. R. (1995). Evaluation of heat and moisture transfer properties in a frozen unfrozen water-soil system. *International Journal of Heat and Mass Transfer*, *38*(12), 2297–2303. https://doi.org/10.1016/0017-9310(94)00283-2

Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, *79*(1), 7–31. https://doi.org/10.1016/j.still.2004.03.008

Skierszkan, E. K., Carey, S. K., Jackson, S. I., Fellwock, M., Fraser, C., & Lindsay, M. B. J. (2024). Seasonal controls on stream metal(loid) signatures in mountainous discontinuous permafrost. *Science of the Total Environment*, *908*, 167999. https://doi.org/10.1016/j.scitotenv.2023.167999

Smith, A., Tetzlaff, D., Laudon, H., Maneta, M., & Soulsby, C. (2019). Assessing the influence of soil freeze–thaw cycles on catchment water storage–flux–age interactions using a tracer-aided ecohydrological model. *Hydrology and Earth System Sciences*, *23*(8), 3319–3334. https://doi.org/10.5194/hess-23-3319-2019

Smith, S. L., O'Neill, H. B., Isaksen, K., Noetzli, J., & Romanovsky, V. E. (2022). The changing thermal state of permafrost. *Nature Reviews Earth & Environment*, *3*(1), 10–23. https://doi.org/10.1038/s43017-021-00240-1

Somers, L. D., & McKenzie, J. M. (2020). A review of groundwater in high mountain environments. *Wiley Interdisciplinary Reviews: Water*, *7*(6), e1475. https://doi.org/10.1002/wat2.1475

Song, L., Wang, L., Zhou, J., Luo, D., & Li, X. (2022). Divergent runoff impacts of permafrost and seasonally frozen ground at a large river basin of Tibetan Plateau during 1960–2019. *Environmental Research Letters*, *17*(12), 124038. https://doi.org/10.1088/1748-9326/aca4eb

Song, Y., Zou, Y. C., Wang, G. P., & Yu, X. F. (2017). Altered soil carbon and nitrogen cycles due to the freeze-thaw effect: A meta-analysis. *Soil Biology and Biochemistry*, *109*, 35–49. https://doi.org/10.1016/j.soilbio.2017.01.020

Sorensen, P. O., Finzi, A. C., Giasson, M., Reinmann, A. B., Sanders-DeMott, R., & Templer, P. H. (2018). Winter soil freeze-thaw cycles lead to reductions in soil microbial biomass and activity not compensated for by soil warming. *Soil Biology and Biochemistry*, *116*, 39–47. https://doi.org/10.1016/j.soilbio.2017.09.026

Spaans, E. J., & Baker, J. M. (1996). The soil freezing characteristic: Its measurement and similarity to the soil moisture characteristic. *Soil Science Society of America Journal*, *60*(1), 13–19. https://doi.org/10.2136/sssaj1996.03615995006000010005x

Starkloff, T., Larsbo, M., Stolte, J., Hessel, R., & Ritsema, C. (2017). Quantifying the impact of a succession of freeze–thaw cycles on the pore network of a silty clay loam and a loamy sand topsoil using X-ray tomography. *Catena*, *156*, 365–374. https://doi.org/10.1016/j.catena.2017.04.026

Stuurop, J. C., van der Zee, S. E. A. T. M., & French, H. K. (2022). The influence of soil texture and environmental conditions on frozen soil infiltration: A numerical investigation. *Cold Regions Science and Technology*, *194*, 103456. https://doi.org/10.1016/j.coldregions.2021.103456

Sun, Z., Zhao, L., Hu, G., Qiao, Y., Du, E., Zou, D., & Xie, C. (2020). Modeling permafrost changes on the Qinghai-Tibetan plateau from 1966 to 2100: A case study from two boreholes along the Qinghai-Tibet engineering corridor. *Permafrost and Periglacial Processes*, *31*(1), 156–171. https://doi.org/10.1002/ppp.2022

Tang, S., Vlug, A., Piao, S., Li, F., Wang, T., Krinner, G., et al. (2023). Regional and tele-connected impacts of the Tibetan Plateau surface darkening. *Nature Communications*, *14*(1), 32. https://doi.org/10.1038/s41467-022-35672-w

Teepe, R., Brumme, R., & Beese, F. (2001). Nitrous oxide emissions from soil during freezing and thawing periods. *Soil Biology and Biochemistry*, *33*(9), 1269–1275. https://doi.org/10.1016/S0038-0717(01)00084-0

Teufel, B., Sushama, L., Arora, V. K., & Verseghy, D. (2019). Impact of dynamic vegetation phenology on the simulated pan-arctic land surface state. *Climate Dynamics*, *52*(1–2), 373–388. https://doi.org/10.1007/s00382-018-4142-2

Thomas, M., Monhonval, A., Hirst, C., Bröder, L., Zolkos, S., Vonk, J. E., et al. (2023). Evidence for preservation of organic carbon interacting with iron in material displaced from retrogressive thaw slumps: Case study in Peel Plateau, western Canadian Arctic. *Geoderma*, *433*, 116443. https://doi.org/10.1016/j.geoderma.2023.116443

Thompson, L. M., Kuhn, M. A., Winder, J. C., Braga, L. P., Hutchins, R. H., Tanentzap, A. J., et al. (2023). Controls on methylmercury concentrations in lakes and streams of peatland-rich catchments along a 1700 km permafrost gradient. *Limnology & Oceanography*, *68*(3), 583–597. https://doi.org/10.1002/lno.12296

Tian, H., Wei, C., Wei, H., & Zhou, J. (2014). Freezing and thawing characteristics of frozen soils: Bound water content and hysteresis phenomenon. *Cold Regions Science and Technology*, *103*, 74–81. https://doi.org/10.1016/j.coldregions.2014.03.007

Tian, Z. C., Kojima, Y., Heitman, J. L., Horton, R., & Ren, T. S. (2020). Advances in thermo-time domain reflectometry technique: Measuring ice content in partially frozen soils. *Soil Science Society of America Journal*, *84*(5), 1519–1526. https://doi.org/10.1002/saj2.20160

Tokumoto, I., Noborio, K., & Koga, K. (2010). Coupled water and heat flow in a grass field with aggregated Andisol during soil-freezing periods. *Cold Regions Science and Technology*, *62*(2–3), 98–106. https://doi.org/10.1016/j.coldregions.2010.03.005

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A., et al. (2020). Carbon release through abrupt permafrost thaw. *Nature Geoscience*, *13*(2), 138–143. https://doi.org/10.1038/s41561-019-0526-0

van Tiel, M., Aubry-Wake, C., Somers, L., Andermann, C., Avanzi, F., Baraer, M., et al. (2024). Cryosphere-groundwater connectivity is a missing link in the mountain water cycle. *Nature Water*, *2*(7), 624–637. https://doi.org/10.1038/s44221-024-00277-8

Verbyla, D. (2011). Browning boreal forests of western North America. *Environmental Research Letters*, *6*(4), 041003. https://doi.org/10.1088/1748-9326/6/4/041003

Virkkala, A. M., Aalto, J., Rogers, B. M., Tagesson, T., Treat, C. C., Natali, S. M., et al. (2021). Statistical upscaling of ecosystem CO_2 fluxes across the terrestrial tundra and boreal domain: Regional patterns and uncertainties. *Global Change Biology*, *27*(17), 4040–4059. https://doi.org/10.1111/gcb.15659

Viterbo, P., Beljaars, A., Mahfouf, J. F., & Teixeira, J. (1999). The representation of soil moisture freezing and its impact on the stable boundary layer. *Quarterly Journal of the Royal Meteorological Society*, *125*(559), 2401–2426. https://doi.org/10.1002/qj.49712555904

Voigt, C., Marushchak, M. E., Abbott, B. W., Biasi, C., Elberling, B., Siciliano, S. D., et al. (2020). Nitrous oxide emissions from permafrost-affected soils. *Nature Reviews Earth & Environment*, *1*(8), 420–434. https://doi.org/10.1038/s43017-020-0063-9

Wagner-Riddle, C., Rapai, J., Warland, J., & Furon, A. (2010). Nitrous oxide fluxes related to soil freeze and thaw periods identified using heat pulse probes. *Canadian Journal of Soil Science*, *90*(3), 409–418. https://doi.org/10.4141/CJSS09016

Walter Anthony, K., Schneider von Deimling, T., Nitze, I., Frolking, S., Emond, A., Daanen, R., et al. (2018). 21st-century modeled permafrost carbon emissions accelerated by abrupt thaw beneath lakes. *Nature Communications*, *9*(1), 3262. https://doi.org/10.1038/s41467-018-05738-9

Walvoord, M. A., & Kurylyk, B. L. (2016). Hydrologic impacts of thawing permafrost—A review. *Vadose Zone Journal*, *15*(6), 1–20. https://doi.org/10.2136/vzj2016.01.0010

Walvoord, M. A., & Striegl, R. G. (2007). Increased groundwater to stream discharge from permafrost thawing in the Yukon River basin: Potential impacts on lateral export of carbon and nitrogen. *Geophysical Research Letters*, *34*(12), L12402. https://doi.org/10.1029/2007GL030216

Wang, G., Peng, Y., Chen, L., Abbott, B. W., Ciais, P., Kang, L., et al. (2024). Enhanced response of soil respiration to experimental warming upon thermokarst formation. *Nature Geoscience*, *17*(6), 532–538. https://doi.org/10.1038/s41561-024-01440-2

Wang, Y., Chen, Y., Li, P., Zhan, Y., Zou, R., Yuan, B., & Zhou, X. (2022). Effect of snow cover on detecting Spring phenology from satellite-derived vegetation indices in alpine grasslands. *Remote Sensing*, *14*(22), 5725. https://doi.org/10.3390/rs14225725

Wang, Y., Liu, H., Chung, H., Yu, L., Mi, Z., Geng, Y., et al. (2014). Non-growing-season soil respiration is controlled by freezing and thawing processes in the summer monsoon-dominated Tibetan alpine grassland. *Global Biogeochemical Cycles*, *28*(10), 1081–1095. https://doi.org/10.1002/2013gb00476

Wang, Z. W., Wang, Q., Zhao, L., Wu, X. D., Yue, G. Y., Zou, D. F., et al. (2016). Mapping the vegetation distribution of the permafrost zone on the Qinghai-Tibet Plateau. *Journal of Mountain Science*, *13*(6), 1035–1046. https://doi.org/10.1007/s11629-015-3485-y

Watanabe, K., & Kugisaki, Y. (2017). Effect of macropores on soil freezing and thawing with infiltration. *Hydrological Processes*, *31*(2), 270–278. https://doi.org/10.1002/hyp.10939

Watanabe, K., & Wake, T. (2009). Measurement of unfrozen water content and relative permittivity of frozen unsaturated soil using NMR and TDR. *Cold Regions Science and Technology*, *59*(1), 34–41. https://doi.org/10.1016/j.coldregions.2009.05.011

Whalley, W., Ober, E., & Jenkins, M. (2013). Measurement of the matric potential of soil water in the rhizosphere. *Journal of Experimental Botany*, *64*(13), 3951–3963. https://doi.org/10.1093/jxb/ert044

Wolf, B., Zheng, X., Brüggemann, N., Chen, W., Dannenmann, M., Han, X., et al. (2010). Grazing-induced reduction of natural nitrous oxide release from continental steppe. *Nature*, *464*(7290), 881–884. https://doi.org/10.1038/nature08931

Woo, M. K. (2012). *Permafrost hydrology* (Vol. 563). Springer.

Woo, M. K., Arain, M. A., Mollinga, M., & Yi, S. (2004). A two-directional freeze and thaw algorithm for hydrologic and land surface modelling. *Geophysical Research Letters*, *31*(12), L12501. https://doi.org/10.1029/2004GL019475

Wright, S. N., Thompson, L. M., Olefeldt, D., Connon, R. F., Carpino, O. A., Beel, C. R., & Quinton, W. L. (2022). Thaw-induced impacts on land and water in discontinuous permafrost: A review of the Taiga Plains and Taiga Shield, northwestern Canada. *Earth-Science Reviews*, *232*, 104104. https://doi.org/10.1016/j.earscirev.2022.104104

Wu, B., Zhu, H. H., Cao, D. F., Xu, L., & Shi, B. (2021). Feasibility study on ice content measurement of frozen soil using actively heated FBG sensors. *Cold Regions Science and Technology*, *189*, 103332. https://doi.org/10.1016/j.coldregions.2021.103332

Wu, M., Ran, Y., Jansson, P. E., Chen, P., Tan, X., & Zhang, W. (2019). Global parameters sensitivity analysis of modeling water, energy and carbon exchange of an arid agricultural ecosystem. *Agricultural and Forest Meteorology*, *271*, 295–306. https://doi.org/10.1016/j.agrformet.2019.03.007

Wu, S., Zhang, Y., & Kang, W. (2024). Employing NDVI as vegetation correction variable to improve soil moisture measurements of mobile cosmic-ray neutron sensor near the Qilian Mountains. *Geoderma*, *441*, 116764. https://doi.org/10.1016/j.geoderma.2023.116764

Wu, X., Zhang, X., Xiang, X., Zhang, K., Jin, H., Chen, X., et al. (2018). Changing runoff generation in the source area of the Yellow River: Mechanisms, seasonal patterns and trends. *Cold Regions Science and Technology*, *155*, 58–68. https://doi.org/10.1016/j.coldregions.2018.06.014

Wu, X. L., & Zhao, Y. (2024). A novel heat pulse method in determining "effective" thermal properties in frozen soil. *Water Resources Research*, *60*(12), e2024WR037537. https://doi.org/10.1029/2024WR037537

Xie, J., Liu, X., Jasechko, S., Berghuijs, W. R., Wang, K., Liu, C., et al. (2024). Majority of global river flow sustained by groundwater. *Nature Geoscience*, *17*(8), 770–777. https://doi.org/10.1038/s41561-024-01483-5

Xie, Z., Liu, S., Zeng, Y., Gao, J., Qin, P., Jia, B., et al. (2018). A high-resolution land model with groundwater lateral flow, water use, and soil freeze-thaw front dynamics and its applications in an endorheic basin. *Journal of Geophysical Research: Atmospheres*, *123*(14), 7204–7222. https://doi.org/10.1029/2018JD028369

Yang, Q., Dan, L., Wu, J., Jiang, R., Dan, J., Li, W., et al. (2018). The improved freeze-thaw process of a climate-vegetation model: Calibration and validation tests in the source region of the Yellow River. *Journal of Geophysical Research: Atmospheres*, *123*(23), 13–346. https://doi.org/10.1029/2017JD028050

Yang, Y., Chen, R., Ye, B., Song, Y., Liu, J., Han, C., & Liu, Z. (2013). Heat and water transfer processes on the typical underlying surfaces of frozen soil in cold regions (i): Model comparison. *Journal of Glaciology and Geocryology*, *35*(6), 1545–1554. https://doi.org/10.7522/j.issn.1000-0240.2013.0171

Yi, J., Zhao, Y., Shao, M. A., Zhang, J., Cui, L., & Si, B. (2014). Soil freezing and thawing processes affected by the different landscapes in the middle reaches of Heihe River Basin, Gansu, China. *Journal of Hydrology*, *519*, 1328–1338. https://doi.org/10.1016/j.jhydrol.2014.08.042

Yi, S., Woo, M. K., & Arain, A. M. (2007). Impacts of peat and vegetation on permafrost degradation under climate warming. *Geophysical Research Letters*, *34*(16), L16504. https://doi.org/10.1029/2007GL030550

Yokohata, T., Saito, K., Takata, K., Nitta, T., Satoh, Y., Hajima, T., et al. (2020). Model improvement and future projection of permafrost processes in a global land surface model. *Progress in Earth and Planetary Science*, *7*(1), 69. https://doi.org/10.1186/s40645-020-00380-w

Young, N. L., Lemieux, J. M., Delottier, H., Fortier, R., & Fortier, P. (2020). A conceptual model for anticipating the impact of landscape evolution on groundwater recharge in degrading permafrost environments. *Geophysical Research Letters*, *47*(11), e2020GL087695. https://doi.org/10.1029/2020GL087695

Yu, L., Zeng, Y., Wen, J., & Su, Z. (2018). Liquid-vapor-air flow in the frozen soil. *Journal of Geophysical Research-Atmospheres*, *123*(14), 7393–7415. https://doi.org/10.1029/2018JD028502

Yuan, Q., Zhong, W., Yang, Q., Peng, Y., Bolch, T., Wang, Y., et al. (2025). Duration of frozen days show a strong decline in the Northern Hemisphere mainly driven by autumn temperature increase. *Innovation Geoscience*, *3*(1), 100118. https://doi.org/10.59717/j.xinn-geo.2024.100118

Zeng, Y., Su, Z., Wan, L., & Wen, J. (2011). A simulation analysis of the advective effect on evaporation using a two-phase heat and mass flow model. *Water Resources Research*, *47*(10), W10529. https://doi.org/10.1029/2011WR010701

Zhang, L., Ren, F., Li, H., Cheng, D., & Sun, B. (2021). The influence mechanism of freeze-thaw on soil erosion: A review. *Water*, *13*(8), 1010. https://doi.org/10.3390/w13081010

Zhang, T., Barry, R. G., Knowles, K., Heginbottom, J. A., & Brown, J. (1999). Statistics and characteristics of permafrost and ground ice distribution in the Northern Hemisphere. *Polar Geography*, *23*(2), 147–169. https://doi.org/10.1080/10889379909377670

Zhang, W., Zhao, Y., Frouz, J., Xue, P., Li, J., Suo, L., et al. (2026). The impact of precipitation on N_2O emissions during the freeze-thaw cycle in a typical grassland in Inner Mongolia. *Soil and Tillage Research*, *255*, 106774. https://doi.org/10.1016/j.still.2025.106774

Zhang, X., Zhang, M., Lu, J., Pei, W., & Yan, Z. (2016). Study of the freezing and thawing features of soil: Current situation and outlook. *Journal of Glaciology and Geocryology*, *38*(6), 1644–1657. https://doi.org/10.7522/j.issn.1000-0240.2016.0192

Zhang, X. Y., Li, D. Q., Chen, L., Ming, F., & Liu, Y. H. (2021). A new integral model for predicting the hydraulic conductivity of saturated frozen soil. *Journal of Hydrology*, *603*, 126838. https://doi.org/10.1016/j.jhydrol.2021.126838

Zhang, Y., Carey, S. K., & Quinton, W. L. (2008). Evaluation of the algorithms and parameterizations for ground thawing and freezing simulation in permafrost regions. *Journal of Geophysical Research*, *113*(D17), D17116. https://doi.org/10.1029/2007JD009343

Zhao, L., Hu, G., Wu, X., Wu, T., Li, R., Pang, Q., et al. (2021). Dynamics and characteristics of soil temperature and moisture of active layer in the central Tibetan Plateau. *Geoderma*, *400*, 115083. https://doi.org/10.1016/j.geoderma.2021.115083

Zhao, L., Ping, C.-L., Yang, D., Cheng, G., Ding, Y., & Liu, S. (2004). Changes of climate and seasonally frozen ground over the past 30 years in Qinghai-Tibetan Plateau, China. *Global and Planetary Change*, *43*, 19–31. https://doi.org/10.1016/j.gloplacha.2004.02.004

Zhao, Y., & Li, D. (2025). Accelerated permafrost thaw linked to rising river temperature and widening channels. *Geophysical Research Letters*, *52*(1), e2024GL112752. https://doi.org/10.1029/2024GL112752

Zhao, Y., Nishimura, T., Hill, R., & Miyazaki, T. (2013). Determining hydraulic conductivity for air-filled porosity in an unsaturated frozen soil by the multistep outflow method. *Vadose Zone Journal*, *12*(1), 1–10. https://doi.org/10.2136/vzj2012.0061

Zhao, Y., & Si, B. (2019). Thermal properties of sandy and peat soils under unfrozen and frozen conditions. *Soil and Tillage Research*, *189*, 64–72. https://doi.org/10.1016/j.still.2018.12.026

Zhao, Y., Si, B. C., He, H. L., Xu, J. H., Peth, S., & Horn, R. (2016). Modeling of coupled water and heat transfer in freezing and thawing soils, Inner Mongolia. *Water*, *8*(10), 424. https://doi.org/10.3390/w8100424

Zheng, C., Šimůnek, J., Lu, Y. D., Liu, X. H., Shi, C. C., & Li, H. H. (2020). Monitoring and modeling the coupled movement of water, vapor, and energy in arid areas. *Journal of Hydrology*, *590*, 125528. https://doi.org/10.1016/j.jhydrol.2020.125528

Zheng, C., Šimůnek, J., Zhao, Y., Lu, Y., Liu, X., Shi, C., et al. (2021). Development of the Hydrus-1D freezing module and its application in simulating the coupled movement of water, vapor, and heat. *Journal of Hydrology*, *598*, 126250. https://doi.org/10.1016/j.jhydrol.2021.126250

Zheng, G. H., Yang, Y. T., Yang, D., Dafflon, B., Lei, H., & Yang, H. B. (2019). Satellite-based simulation of soil freezing/thawing processes in the northeast Tibetan Plateau. *Remote Sensing of Environment*, *231*, 111269. https://doi.org/10.1016/j.rse.2019.111269

Zhong, W., Zhang, T., Chen, J., Shang, J., Wang, S., Mu, C., & Fan, C. (2021). Seasonal deformation monitoring over thermokarst landforms using terrestrial laser scanning in Northeastern Qinghai-Tibetan Plateau. *International Journal of Applied Earth Observation and Geoinformation*, *103*, 102501. https://doi.org/10.1016/j.jag.2021.102501

Zhou, X., Zhou, J., Kinzelbach, W., & Stauffer, F. (2014). Simultaneous measurement of unfrozen water content and ice content in frozen soil using gamma ray attenuation and TDR. *Water Resources Research*, *50*(12), 9630–9655. https://doi.org/10.1002/2014WR015640

Zhou, Y., Zhou, J., Shi, X. Y., & Zhou, G. Q. (2019). Practical models describing hysteresis behavior of unfrozen water in frozen soil based on similarity analysis. *Cold Regions Science and Technology*, *157*, 215–223. https://doi.org/10.1016/j.coldregions.2018.11.002

Zhu, P., Kim, T., Jin, Z., Lin, C., Wang, X., Ciais, P., et al. (2022). The critical benefits of snowpack insulation and snowmelt for winter wheat productivity. *Nature Climate Change*, *12*(5), 485–490. https://doi.org/10.1038/s41558-022-01327-3

Zhu, X., Jia, G., & Xu, X. (2024). Accelerated rise in wildfire carbon emissions from Arctic continuous permafrost. *Science Bulletin*, *69*(15), 2430–2438. https://doi.org/10.1016/j.scib.2024.05.022