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Integrating surface-active layer-permafrost hydrological processes: A systematic review and research framework

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Abstract. Climate warming has accelerated permafrost degradation, leading to significant challenges in water circulation and transformation. Since the early 21st century, especially during the last ten years, permafrost hydrology has garnered substantial attention, yielding a wealth of research outcomes. However, a comprehensive and systematic understanding of the permafrost hydrology remains limited. This study synthesised the current knowledge through an extensive literature review and systematic analysis, establishing a foundational framework for permafrost hydrology. The framework integrated three critical dimensions: surface hydrological processes, hydrological functions of the active layer, and the hydrological effects of permafrost changes. Subsequently, the current state, trends, and challenges in permafrost hydrology research were summarised, and a holistic overview was provided. Regarding surface hydrological processes in permafrost regions, this study examined the impacts of freeze-thaw cycles on surface runoff from multiple perspectives, including the influence of active layer thawing, slope hydrological processes, river channel dynamics, large-scale permafrost hydrology, and the hydrological consequences of thermokarst formation. For hydrological processes within the active layer, the study identified the hydrological role of the active layer, key factors influencing its hydrological behaviour, and the interactions between suprapermafrost water and soil water. Concerning the hydrological impacts of permafrost thaw, this study investigated the transformation dynamics between surface and groundwater in permafrost regions by analysing the effects of climate change through increased baseflow, groundwater recharge, and subsurface runoff. Finally, this study outlined future research directions, emphasising three key areas: the application of novel observational methods, integrated surface-subsurface investigations, and the ecological and environmental impacts of permafrost hydrological changes.

1 Introduction

Among the environmental elements influenced by global change, the cryosphere is at the forefront and exhibits the most rapid, pronounced, and indicative responses. It is also the most direct and sensitive component of the climate system (Ding

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and Xiao, 2013) and is widely recognised as a critical link in the interactions among multiple spheres of the climate system (IPCC, 2007). Within the cryosphere, permafrost has garnered increasing attention owing to its extensive distribution and profound influence on hydrological processes (Yang et al., 2000; Hinzman et al., 2005; Woo, 2008, 2012, 2019; Kalyuzhnyi and Lavrov, 2012; Liljedahl et al., 2016; Walvoord and Kurylyk, 2016; Wang and Zhang, 2016; AMAP, 2017; Ding et al., 2017, 2020a; Rogger et al., 2017; Chen et al., 2019; Lafrenière and Lamoureux et al., 2019; Zhao et al., 2019; Hiyama et al., 2021a; Makarieva et al., 2021; Ehlers et al., 2022; Jin et al., 2022a).

Permafrost is predominantly distributed in the high-latitude and high-altitude regions of the Northern Hemisphere, where its hydrological impacts are most pronounced. In high-altitude regions of Asia, particularly the Tibetan Plateau, permafrost plays a critical role in shaping hydrological processes in mountainous basins. Estimates indicate that the global maximum storage of ground ice is approximately 36.6×10^3 km³, with a water equivalent of five times the annual discharge of the Amazon River and 35 times that of the Yangtze River (Zhang et al., 1999). On the Tibetan Plateau, the permafrost ice content is estimated at 12.7×10^3 km³ (Zhao et al., 2019), with a water equivalent of 12 times the annual discharge of the Yangtze River. Changes in permafrost can induce significant alterations in water circulation and hydrological processes, profoundly affecting regional ecology and water resources.

Over the past several decades, permafrost has undergone substantial global changes including widespread increases in temperature, reductions in extent, thinning of layers, deepening of the active layer, and increased thermokarst activity (Cheng et al., 2019; Zhao et al., 2008, 2019, 2020, 2023; IPCC, 2019; van Huissteden, 2020; Jin et al., 2022a). These changes have already exerted notable impacts on hydrological processes, such as increased winter runoff and enhanced river discharge due to permafrost thaw (Ye et al., 2009, 2012; Niu et al., 2011; AMAP, 2017; Chen et al., 2019; Tang et al., 2019; Song et al., 2020a; Tananaev and Lotsari, 2022). However, many of these findings are based on indirect methods and involve qualitative assessments with considerable uncertainty.

Nevertheless, as climate warming continues, the hydrological impacts of permafrost change have become increasingly critical. These impacts are relevant not only for water resource management, but also for understanding ecological changes in cold regions and the dynamics of water resources. Furthermore, changes in permafrost hydrology are closely linked to the carbon and nitrogen cycles, hydrogeochemical processes, and water environment dynamics (Hinzman et al., 2005; O'Donnell et al., 2012, 2019, 2024; Walvoord and Kurylyk, 2016; Ma et al., 2019; Wang and Yi, 2019; Yang and Kane, 2021; Ehlers et al., 2022; Li et al., 2022; Shirley et al., 2022; Varner et al., 2022; Wang et al., 2023). Therefore, systematic research on the hydrological impacts of permafrost changes, is not only essential for water resource studies in cold regions, but also fundamental to understanding ecological changes, carbon and nitrogen cycles, and water environment dynamics in permafrost regions.

The hydrological effects of permafrost are multifaceted and encompass changes in soil moisture, hydrological connectivity, seasonal runoff distribution, surface runoff generation and concentration processes, and groundwater storage (Walvoord and Kurylyk, 2016). In summary, the hydrological role of permafrost can be categorized into three aspects (Ding et al., 2020a, 2020c; Tananaev et al., 2020): **(1) Hydrological Effect of the Surface Underlying Layer:** The frozen surface

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in permafrost regions acts as a significant barrier to water flow, particularly during winter and spring. This barrier increases surface runoff during snowmelt or rainfall events; **(2) Regulatory Role of the Active Layer on Runoff:** The development and seasonal thawing of permafrost determine the depth of the active layer, which in turn influences infiltration, water storage, and subsurface runoff processes; and **(3) Water Supply Function:** The large volume of ice stored in permafrost acts as a long-term water reservoir. Permafrost degradation leads to the release of this ice as liquid water, contributing to river discharge through subsurface flow. Thus, permafrost changes have complex and far-reaching effects on hydrological processes, significantly affecting both surface and subsurface water dynamics.

In conclusion, the relationship between permafrost and hydrological processes is intricate and multifaceted, influencing said processes from the surface to the active layer and permafrost table through various means. Although surface runoff in permafrost regions can be directly observed through slope hydrological experiments (Chen et al., 2014), hydrological processes within the active layer and permafrost are difficult to observe directly. Consequently, statistical analysis, modelling, geophysical exploration, and isotope tracing have become the primary methods for studying these processes (Wu et al., 2005; Karra et al., 2013; Painter et al., 2013; Li et al., 2016, 2020; Ding et al., 2017; Gibsona et al., 2019; Song et al., 2020b; Sun et al., 2020; Gao et al., 2021, 2022; Gao and Coon, 2022; Xu and Gao, 2022). Since the early 21st century, especially during the last ten years, substantial advancements have been made in permafrost hydrology research, largely owing to the development and refinement of innovative methodologies. This study consolidated the existing research by conducting an extensive literature review and systematic analysis. It offers a holistic overview of the current understanding of permafrost hydrology, focusing on surface hydrological processes, active layer dynamics, and hydrological impacts of permafrost changes. By integrating these perspectives, this study provides a comprehensive framework for understanding the complex interactions and feedback mechanisms within permafrost-influenced hydrological systems.

2 Permafrost and surface hydrological processes

Surface freeze-thaw cycles significantly influence the generation and concentration of surface runoff, altering the runoff coefficients, particularly during the spring thaw and autumn freeze of the active layer. In addition, thermokarst processes modify the underlying surface characteristics, further affecting hydrological connectivity and runoff dynamics.

2.1 Impact of freeze-thaw cycles on surface runoff

From spring to summer, as the active layer thaws, the infiltration capacity of the soil increases, reducing direct surface runoff. Conversely, in autumn, soil infiltration is restricted as the surface begins to freeze, leading to increased surface runoff. These freeze-thaw cycles play a critical role in shaping slopes, river channels, and large-scale surface hydrological processes.

Impact of Active Layer Thawing on Surface Runoff: Soil freezing impedes water infiltration and increases surface runoff during spring snowmelt or rainfall. This can lead to soil erosion and delayed solute transport into the deeper soil layers (Shirley et al., 2022; Tananaev and Lotsari, 2022). Given the close relationship between snow and permafrost, spring

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thawing of the active layer significantly influences snowmelt hydrological processes (Zhang et al., 2017; Du et al., 2019). Moreover, soil moisture dynamics during snowmelt are more complex than those during summer rainfall. Water infiltrating frozen soil provides latent heat, increasing the soil temperature and liquid water content (Yang et al., 2019a). Conversely, the refreezing of meltwater at the surface and within the active layer reduces infiltration rates (Bayard et al., 2005), whereas the presence of pore ice weakens the soil infiltration capacity, leading to increased surface runoff and reduced groundwater recharge. In summer, as the active layer deepens, the surface water infiltration increases, significantly reducing the surface runoff. Studies on small watersheds in the northern Tibetan Plateau have shown that summer runoff is intermittent, with most runoff events lasting less than 24 h. Precipitation events without runoff are typically associated with low soil-moisture conditions (Gao et al., 2018a). Model simulations have further demonstrated that surface runoff is strongly dependent on seasonal variations in precipitation and temperature. Increased spring-summer runoff is primarily driven by snowmelt and active layer thaw, whereas permafrost limits deep infiltration, leading to an increased groundwater contribution during thaw (Ahmed et al., 2022). Thus, surface runoff in permafrost regions is influenced by complex interactions between soil temperature, antecedent soil moisture, thaw depth, spring snowpack, summer precipitation frequency and intensity, and other factors.

Hillslope Hydrological Processes: Permafrost plays a crucial role in the modulation of water infiltration, flow, and sediment transport on slopes. It influences the balance between advective fluvial and diffusive processes in ways that are distinct from those in temperate regions (Tananaev and Lotsari, 2022; Vecchio et al., 2024). Watersheds in permafrost regions exhibit lower drainage densities than those in non-permafrost regions, likely because frozen soil inhibits channel development. Climate warming is expected to lower the incision thresholds and promote the growth of channel networks in permafrost landscapes (Tananaev and Lotsari, 2022; Vecchio et al., 2024). Thawing permafrost, melting ground ice, and changing hydrological regimes can expand channel networks and enhance hydrological connectivity (Rowland, 2023). Studies on the Niaqunguk River watershed in Nunavut, Canada have revealed that the hillslope structure and thaw processes create distinct fill-and-spill domains. Surface and subsurface domains influence sporadic hillslope-stream connections during periods of sufficient rainfall and saturation (Chiasson-Poirier et al., 2020). Observations from 11 headwater streams in Alaska have shown that hillslopes with continuous permafrost have shallower flow paths and higher evapotranspiration rates than non-permafrost hillslopes (Sjöberg et al., 2021). These findings indicate that freeze-thaw processes are closely linked to hillslope hydrological connectivity and runoff patterns, and climate change is likely to significantly alter these processes.

River Channel Hydrological Processes: Seasonal changes in channel morphology are becoming more pronounced in permafrost-controlled valleys and river channels. Higher low bank and reduced high bank retreat rates lead to accelerated floodplain subsidence (Tananaev and Lotsari, 2022). Permafrost degradation weakens riverbanks, increasing lateral channel mobility. Studies have indicated that the lateral migration of large Arctic rivers has decreased by approximately 20% over the past half-century. This trend is driven by atmospheric warming, which has indirect effects such as bank shrubification, reduced overland flow, and seepage discharge along channel banks (Ielpi et al., 2023). In the Low Arctic, permafrost thaw and talik formation alter streamflow regimes, with riparian shrub expansion indicating widespread change (Liljedahl et al.,

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2020). Aufeis (icing), formed from groundwater discharge, is an important component of water storage. For example, winter aufeis volumes account for 27–30% of the annual groundwater discharge in the Arctic Kuparuk River (Yoshikawa et al., 2007). These findings underscore the stable, long-term, and continuous contribution of aufeis to surface-water recharge.

Large-Scale Permafrost Hydrological Processes: The presence or absence of permafrost significantly influences soil water storage capacity on a large scale, determining whether water cycles are driven by hydrological or ecological processes (Ding et al., 2000; Young-Robertson et al., 2021). In continuous permafrost regions, hydrological processes are primarily controlled by the active layer depth and soil water storage capacity (Fig. 1a). In discontinuous permafrost zones, hydrological processes exhibit a transitional shift from being dominated by active layer thickness and soil water storage capacity to increasing ecological regulation (Fig. 1b), with varying hydrological-ecological linkages contingent upon the degree of permafrost degradation. In sporadic or isolated permafrost and seasonal frost regions, ecological processes play a significant role in influencing the surface runoff capacity (Fig. 1c). In low-gradient watersheds underlain by continuous permafrost, evapotranspiration often exceeds precipitation during the summer months, leading to the drying of extensive wetlands and the fragmentation of drainage networks (Kane and Gieck, 2003). The modelling results indicate that rapid permafrost thaw can lead to soil drying, surface warming, and reduced relative humidity in the Arctic-Subarctic regions (Kim et al., 2024). Land-cover changes resulting from permafrost degradation have a substantial impact on runoff. For example, studies in northwestern Canada have shown that land-cover change is the single most important factor contributing to increased runoff, accounting for approximately 35% of the total increase (Connon et al., 2014). Increased rainfall accelerates permafrost thaw, with observations in Alaska indicating that each additional centimetre of rain leads to 0.7 ± 0.1 cm of additional thaw, particularly in disturbed and wetland sites (Douglas et al., 2020). Permafrost thaw also increases river discharge, with Arctic-wide studies demonstrating significant increases in water export and changes in spring freshet and summer stream intermittency (Feng et al., 2021).

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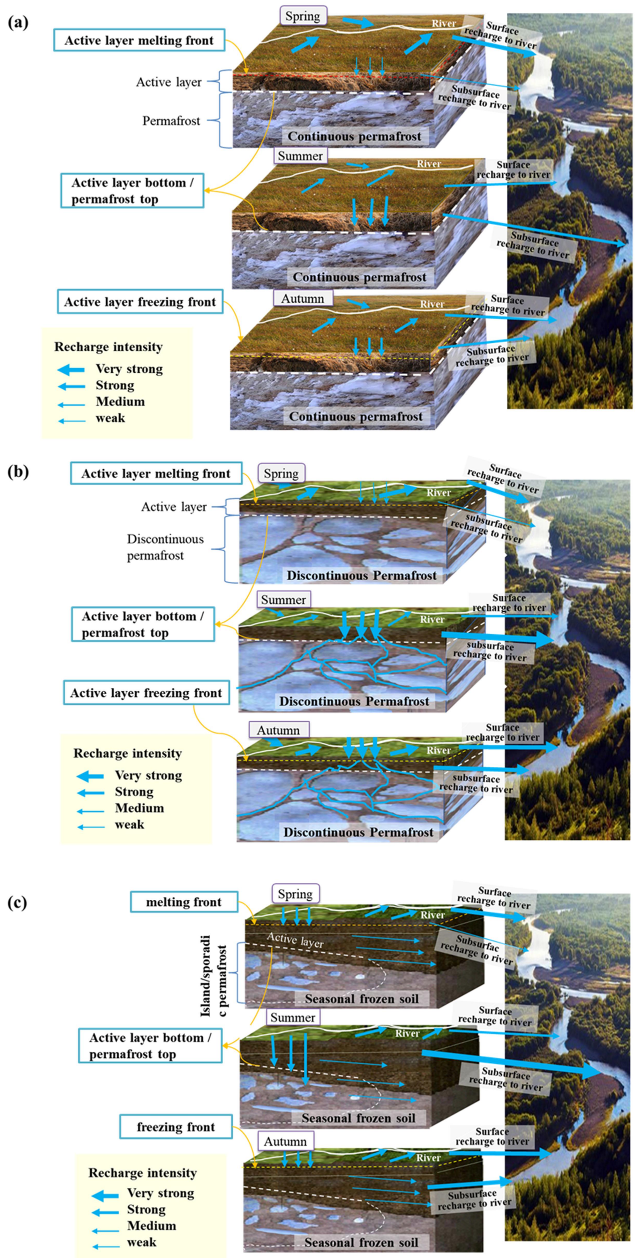

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Figure 1: Impact of freeze-thaw cycles on surface hydrological processes. (a) Dominance of active layer depth and soil water storage capacity, (b) Transition from dominance of active layer depth and soil water storage capacity to ecological dominance, and (c) Ecological dominance.

Active Layer as Hydrological Control Hub: The active layer serves as the primary regulator of surface runoff partitioning, with its thaw state dictating the dominance of saturation-excess versus infiltration-excess flow. Critically, surface runoff contributions exhibit threshold behavior tied to ground ice content. When volumetric ice content >40%, hydraulic transmissivity drops exponentially ($K_{eff} = K_{sat} \cdot e^{-0.21.ICEv}$; Kendall, 1999), forcing >80% of meltwater into surface runoff. Below 25% ice content, subsurface flow dominates (≥70% of total discharge). This explains why undisturbed High Arctic slopes exhibit negligible surface runoff (<10% of annual discharge; Lewkowicz & French, 1982), while thermokarst-disturbed areas experience >40% surface runoff (Kokelj & Lewkowicz, 1998). Permafrost disturbance fundamentally alters hillslope water tracks—the key conduits connecting surface and subsurface flow—by accelerating their evolution from discontinuous pipes (Stage I) to integrated channel networks (Stage III) (Stieglitz et al., 2003).

2.2 Hydrological effects of permafrost thermokarst

With ongoing climate warming, thermokarst processes in permafrost regions have intensified and are primarily characterised by changes in thermokarst lakes and ponds. In the Arctic, the northward expansion of beavers into tundra regions has resulted in the formation of numerous beaver ponds that exhibit hydrological and ecological effects similar to those of thermokarst lakes and ponds (Tape et al., 2022). Current research indicates that changes in thermokarst lakes are highly heterogeneous, with certain regions experiencing an increase in their number and extent (Farquharson et al., 2019; Zhou et al., 2024), whereas others have shown a decline (Gramling, 2015; Liu et al., 2023). On the Tibetan Plateau, thermokarst lakes are predominantly developed in warm permafrost regions (Liu et al., 2023; Zhou et al., 2024), whereas thermokarst features are extensively distributed in the extremely cold permafrost areas of the High Arctic (Farquharson et al., 2019). Despite these regional variations, the hydrological impacts of thermokarsts are profound. Thermokarst processes modify surface water dynamics, enhance water exchange between the surface and the atmosphere, influence soil water infiltration, and facilitate the transformation between surface water and groundwater (Fig. 2).

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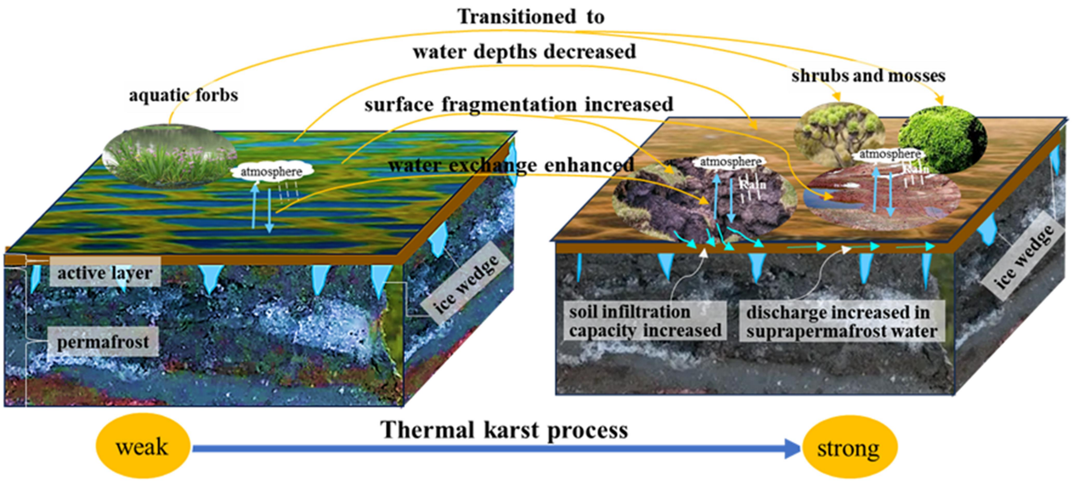

Figure 2: Hydrological effects of permafrost thermal karst processes.

Rapid Changes in Surface Cover and Hydrological Processes: Thermokarst processes can induce dramatic and rapid alterations in surface cover with profound hydrological and ecological consequences. For example, thermokarst activity has significantly transformed the Tanana Flats of central Alaska, increasing the area of large fens by 26% between 1949 and 2018 (Jorgenson et al., 2020). Similarly, in the Canadian High Arctic, above-average summer warmth triggered rapid landscape responses, including substantial subsidence, owing to limited thermal buffering from overlying ecosystem components and near-surface ground ice (Farquharson et al., 2019). In the peaty-silty lowlands of Canada, a thaw settlement of 2–4 m has disrupted drainage patterns, resulting in widespread soil flooding and the accumulation of new bog peat (Jorgenson et al., 2013). Conversely, in the headwater area of the Yellow River, the number of water bodies larger than 0.36 ha decreased by 40%, accompanied by a 25% reduction in total surface area from 1986–2015 (Șerban et al., 2021). These examples highlight the rapid and far-reaching impacts of thermokarst activity on hydrological, ecological, and biogeochemical processes.

Enhanced Connectivity Between Permafrost and Surface Water: Long-term water balance analyses indicate that, in Arctic thermokarst regions, groundwater recharge primarily occurs through taliks, with surface processes dominated by evapotranspiration during the thaw period and snow control during the freeze period (Lindborg et al., 2013). Observations and surveys have documented a rapid increase in the number of thermokarst lakes on the Tibetan Plateau from 1969–2010, which was largely driven by the expansion of both small ponds and large lakes (Luo et al., 2015). Research has demonstrated that under climate warming, the expansion of thermokarst lakes is closely linked to increased suprapermafrost water runoff (Lindborg et al., 2013; Yang et al., 2016, 2017; Pan et al., 2017; Gao et al., 2018a, 2018b). Stable isotope analyses and

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modelling studies have revealed significant hydrological connections between precipitation, river water, thermokarst lakes, and permafrost ice melt (Yang et al., 2017). Data from 2011–2012 highlighted that permafrost melt contributed approximately 61% of the water in thermokarst lakes (Yang et al., 2016), emphasising the critical role of permafrost degradation in lake development on the Tibetan Plateau. Despite these advancements, the hydrological relationships between subpermafrost, suprapermafrost, and surface water remain poorly understood, particularly as permafrost degradation intensifies. Thus, the hydrological interactions between thawed zones and permafrost require further investigation (Fig. 2).

Enhanced Hydrological Connectivity by Thermokarst: Thermokarst activity significantly enhanced hydrological connectivity. During the ice-free season, precipitation and active-layer hydrology are the primary drivers of hydrological change. However, under ice cover, the hydrology of thermokarst lakes is predominantly controlled by the melting of surrounding permafrost, including ground ice (Yang et al., 2019b; Șerban et al., 2021). Thermokarst lakes induce notable changes in the soil infiltration processes. Specifically, the initial infiltration rate decreased as the impact of the thermokarst intensified, whereas the stable and cumulative infiltration rates gradually increased in the surface layer at depths of 10 and 20 cm. These parameters initially decreased and then increased, showing a significant correlation with soil texture. Furthermore, the cumulative infiltration changes align with a steady infiltration rate (Wang et al., 2014). In the Taiga Plain, permafrost is predominantly associated with peatlands. The thawing of this permafrost expands the extent of thermokarst wetlands, often at the expense of the treed peatlands underlying the permafrost. This thaw-induced land cover change enhances landscape-scale hydrological connectivity, increases basin-scale runoff and annual streamflow, and promotes wetter conditions (Wright et al., 2022). Additionally, the rapid drainage of thaw lakes has been identified as a potential issue in many circumpolar Arctic regions (Pohl et al., 2009). Areas with taliks experience more rapid thawing of the underlying permafrost than areas without taliks (Connon et al., 2018). These processes result in the formation of new thermokarst lakes and the drainage of existing lakes, along with significant changes in seasonal hydrology. For example, in northwestern Siberia, the continuous-to-sporadic permafrost underlying the tundra and taiga landscapes of the Nadym and Pur river basins has significantly warmed in recent decades. Both basins exhibit reduced discharge variability, reflecting substantial changes in their hydrological storage-discharge dynamics due to permafrost thaw, which also alters their thermokarst lakes (Karlsson et al., 2011). Moreover, recent reductions in pond and lake areas in discontinuous permafrost regions have been linked to increased subsurface drainage and connectivity (Smith et al., 2010, 2012; Derksen et al., 2018).

3 Hydrological processes within the active layer

In permafrost regions, the freeze-thaw cycles of the active layer not only influence the generation and concentration of surface runoff but also modulate subsurface flow and interflow within the active layer, ultimately affecting the recharge and runoff processes of suprapermafrost water (Ding et al., 2020b, 2020c; Qin et al., 2024). Suprapermafrost water is primarily recharged by surface snowmelt and rainfall infiltration (Chang et al., 2015; Yang et al., 2017; Cao et al., 2018), as well as by

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water released from thawing permafrost (Wang et al., 2017, 2018d; Gao et al., 2018b; Zhao et al., 2019; Halla et al., 2020; Ma et al., 2021a; Hilbich et al., 2022).

Hydrological Role of the Active Layer: Studies have demonstrated that the annual processes within the active layer exert significant hydrological impacts (Fig. 3) (Cooper et al., 2011; Lacelle and Vasil'chuk, 2013; Wang et al., 2017; Gao et al., 2018b; Ding et al., 2020b; Cao et al., 2021a). Water within the active layer comprises surface snowmelt, rainfall infiltration, soil water, and suprapermafrost water (Chang et al., 2015; Yang et al., 2017; Cao et al., 2018). Rainfall infiltration serves as the primary driver of soil hydrological processes, with the freeze-thaw front acting as the main limiting factor. During spring, as the surface temperature rises above zero, the active layer begins to thaw, which coincides with snowmelt. In the initial thaw phase, the shallow thaw front and low soil temperatures caused infiltrating snowmelt to refreeze, significantly reducing infiltration rates. During this stage, the active layer functioned as an impermeable barrier, leading to high surface runoff coefficients and substantial snowmelt runoff (Fig. 3). In the mid-thaw phase, as soil temperatures increase and the thaw front deepens, water from surface snowmelt and soil thaw accumulates above the thaw front, forming shallow groundwater within the active layer. As the active layer deepens, the soil infiltration capacity increases, allowing snowmelt or rainfall to rapidly infiltrate. This process elevates soil moisture levels and triggers a rapid increase in shallow groundwater levels. Groundwater storage and flow capacity increase linearly with active layer depth, whereas subsurface runoff gradually increases, and surface runoff coefficients decrease. In the late thaw phase, as the active layer continues to deepen, the soil pore space expands, and precipitation infiltration becomes the primary source of groundwater recharge, replacing meltwater. This shift has led to the formation of precipitation-dominated subsurface runoff. During this stage, groundwater levels gradually decrease, and the upper soil layers begin to dry. By September, the active layer is fully thawed, and suprapermafrost water accumulates above the permafrost table. The height of the suprapermafrost water table is strongly influenced by the amount of precipitation recharge during the earlier stages.

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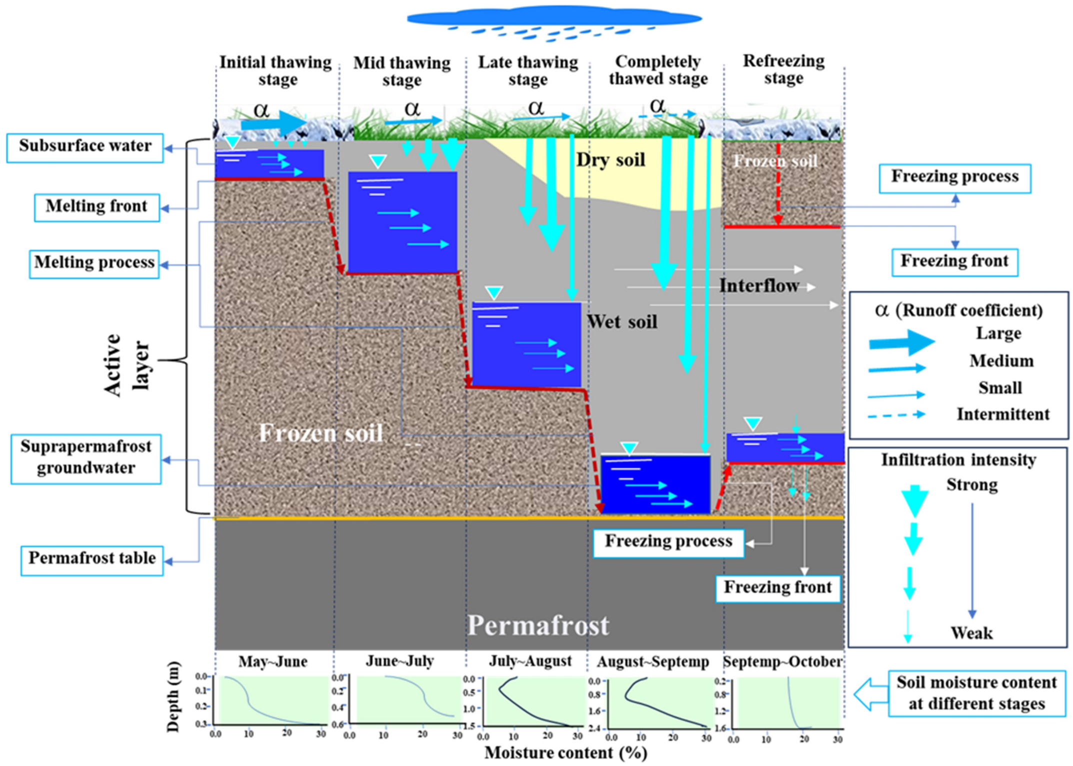

Figure 3: Hydrological processes within the active layer (adapted from Ding et al., 2020b; Qin et al., 2024).

The impact of the active layer on surface runoff is most pronounced during the spring thaw and autumn freeze periods. During the spring thaw, surface snowmelt or precipitation often generates runoff through saturation-excess overland flow, which dominates surface runoff in the early thaw phase. In the mid-thaw phase, as the soil infiltration capacity increases, the surface runoff transitioned from saturation-excess to infiltration-excess overland flow. During the late and fully thawed phases, soil drying allows rapid precipitation infiltration, making surface runoff intermittent and limited to heavy rainfall events. In autumn, as the surface begins to freeze, soil infiltration decreases, and surface runoff reverts to saturation-excess overland flow (Zhang et al., 2016; Wang et al., 2017; Gao et al., 2022). Driven by the temperature gradient, unfrozen water in the active layer migrates from bottom to top during the freezing stage. These dynamics demonstrate that runoff generation in permafrost regions involves multiple mechanisms controlled by temperature, and exhibits distinct seasonal variations. Observations and simulations of small watersheds on the Tibetan Plateau have revealed distinct seasonal hydrological

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dynamics. During the spring flood period, the soil temperature and moisture at depths above 65 cm play a dominant role. In contrast, during the summer dry period, the soil moisture above 40 cm is negatively correlated with runoff, whereas deep soil temperature and moisture are the primary controlling factors. Air temperature and precipitation are the main drivers of hydrological processes during the summer flood period (Li et al., 2009). During the spring thaw, saturation-excess overland flow accounts for 66–85% of the total spring runoff, and interflow within the active layer contributes 14–34%. In the autumn runoff recession period, suprapermafrost groundwater runoff decreases rapidly as the active layer freezes, leading to an increase in the proportion of subsurface to total runoff and higher surface runoff coefficients (Bai et al., 2012; Wang et al., 2017). In the northern wetlands of Canada, the storage capacity in continuous permafrost regions increases during summer as evaporation reduces the peat moisture content. The subsurface flow remains minimal owing to low hydraulic gradients and conductivity. Consequently, when the water table lies within the peat layer, the contribution of wetlands to streamflow is negligible. However, during intense storms, when the water table rises above the ground surface, streamflow increases rapidly owing to the surface flow across the wetlands (Roulet and Woo, 1986).

Key Factors Influencing Hydrological Processes in the Active Layer: The primary factors influencing the hydrological processes in the active layer include permafrost type, underlying surface characteristics, topography, and soil composition. Understanding the hydrological processes in permafrost regions requires an integrated analysis of both water and heat balance relationships (Wang et al., 2017; Zhang et al., 2017; Gao et al., 2021, 2022). Soil physical properties play critical roles in regulating soil water and heat dynamics in these regions (Zhang et al., 2017; Yang et al., 2019a). Observations indicate that as vegetation cover decreases, soil moisture decreases at depths of 0.2–0.6 m in the active layer but increases at depths of 0.6–0.8 m. In seasonal permafrost, soil moisture increases with depth throughout the profile (0.2–1.0 m). Thus, changes in vegetation cover significantly alter the soil water and heat processes, although the effects differ between permafrost and seasonal frost (Hu et al., 2009). Observations and simulations have demonstrated that the initial, stable, and cumulative soil infiltration rates are strongly influenced by the underlying surface types. The highest initial and stable infiltration rates were observed in the alpine desert steppes, whereas the lowest rates were observed in the alpine meadows. Within the same underlying surface, the infiltration parameters increase with vegetation cover, whereas soil moisture and infiltration rates exhibit opposite trends (Wang et al., 2014; Hu et al., 2018). Soil organic matter plays a dual role by providing both insulating and water-retaining effects. Its content in the active layer not only mitigates deepening, but also significantly influences water movement (Roulet and Woo, 1986; Karra et al., 2013; Hu et al., 2015; Kalyuzhnyi and Lavrov, 2017; Tananaev et al., 2022). Simulations of soil moisture in permafrost regions revealed that despite increases in net atmospheric surface water flux (P-ET), most models predict long-term drying of surface soils (0–20 cm) owing to active layer deepening or permafrost thaw. This suggests that future increases in precipitation may not fully offset the effects of active-layer deepening on surface soil moisture reduction (Andresen et al., 2020). In summary, water movement within the active layer is a complex process shaped by the interactions between water and heat dynamics, active-layer thickness, permafrost type, soil composition, and vegetation cover.

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Interactions Between Suprapermafrost Water and Soil Water: The interaction between suprapermafrost water and soil water is a critical component of hydrological processes in permafrost regions. Hydrological dynamics within the active layer are not only driven by freeze-thaw phase changes but are also closely linked to unconfined groundwater dynamics. During freeze-thaw cycles, surface and subsurface runoff undergo redistribution and transformation, resulting in frequent short-term fluctuations in surface and subsurface storage (Tananaev et al., 2020; Cao et al., 2021a, 2021b). Simulations in the source region of the Lancang River demonstrated that cold-season warming increases liquid soil moisture in seasonal permafrost, whereas warm-season warming primarily drives active layer thickening, increasing the liquid water content in permafrost. Cold-season warming has a greater impact because of its significant role in accelerating permafrost degradation (Xu and Gao, 2022). For liquid soil moisture, increases during cold months are attributed to rising soil temperatures and enhanced soil ice melting, whereas changes during warm months result from competition between positive precipitation and negative soil temperature effects (Cuo et al., 2015). These findings highlight the interdependence of suprapermafrost water and soil water-heat dynamics (Cao et al., 2018; Du et al., 2019; Yi et al., 2021). The interflow within the active layer migrates downward and accumulates above the permafrost table. This accumulated suprapermafrost water not only generates subsurface runoff through gravitational drainage but also interacts with permafrost through water exchange. Infiltration of groundwater from the surface carries heat, leading to the partial melting of permafrost, whereas a portion of the groundwater freezes and is incorporated into permafrost (Wang et al., 2017, 2018d; Yang et al., 2017; Gao et al., 2018a; Zhao et al., 2019; Halla et al., 2020; Ma et al., 2021b; Hilbich et al., 2022). Under long-term stable conditions, the amounts of melted permafrost and frozen groundwater remain balanced. Studies on the Tibetan Plateau have revealed that active-layer water accounts for 59–87% of the ground ice near the permafrost table, whereas permafrost water contributes 13–41%, which indicates that the active layer plays a significant role in ground ice formation, with alpine meadows contributing less (59–69%) than alpine steppes (70–87%) (Wang et al., 2018c). Simulations of daily runoff in the Yenisei River, the largest Arctic river in central Siberia, demonstrated that subsurface runoff within the active layer significantly contributes to river recharge (Fabre et al., 2017), underscoring the critical role of subsurface runoff in sustaining river flow. Permafrost hydrology is significantly influenced by suprapermafrost water, as a portion of ground ice is melted and integrated into the active layer hydrological processes. The seasonal dynamics and movement of suprapermafrost water are primarily regulated by soil temperature, whereas its phase changes depend on deep soil moisture and the sources of suprapermafrost water recharge. The relationship between active layer soil temperature and suprapermafrost water table dynamics can be effectively characterised by the Boltzmann function (Chang et al., 2015).

In summary, the active layer is critical interface between surface and suprapermafrost water, playing a pivotal role in the hydrological impacts of permafrost change. However, current research on the influence of the active layer water-heat processes on major hydrological processes–-such as surface runoff generation, large-scale flow concentration, suprapermafrost water phase changes, subsurface runoff processes, and surface-groundwater connectivity—remains in its early stages. Therefore, the underlying mechanisms and quantitative relationships require further investigation.

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4 Impacts of permafrost degradation on groundwater and surface runoff

As climate warming intensifies, permafrost degradation accelerates. This degradation inevitably releases ground ice as liquid water, which subsequently participates in the transformation and cycling of surface and groundwater. Unlike glacial or snowmelt, the volume of water released from permafrost thaw is difficult to measure directly, and its impact on runoff and water resources within watersheds remains poorly understood.

4.1 Transformation relationships between surface water and groundwater in permafrost regions

Water-age determination has emerged as a novel approach for inferring the hydrological impact of permafrost degradation. Wang et al. (2023) applied sinusoidal wave methods and gamma models based on seasonal cycles of stable isotopes in water to estimate the water-age composition and mean transit times in the Buqu River Basin and its 23 sub-basins in the Yangtze River source region. Their findings revealed that water ages were shorter in high-altitude and glacial regions, but longer in low-altitude and non-glacial sub-basins. Precipitation was identified as the primary driver of spatial variations in water age, whereas the thickness of the active layer likely played a central role in controlling the water age by altering the flow direction and path length. These results suggest that cryospheric retreat may decelerate the water cycle by increasing water age. Arctic studies have also demonstrated a strong correlation between the permafrost age and runoff, enabling the identification of permafrost thaw trends, groundwater age, and water balance in Arctic permafrost basins using long-term runoff data (e.g. Hiyama et al., 2021a). Residence times for pore water in the suprapermafrost aquifer (shallow) are on the order of 10 years, compared to 10^3–10^4 years for pore water in subpermafrost aquifers (Walvoord et al., 2012). In addition, ice wedges (or aufeis) serve as important indicators of the connection between groundwater and surface water in permafrost regions. The volume of aufeis stored on and below the surface cannot be overlooked in regional runoff estimates (Gagarin et al., 2022). In thermokarst regions, significant amounts of ground-ice meltwater are detected in springs, reflecting the linkage between surface water and groundwater (Hiyama et al., 2021b). Thus, aufeis and springs provide critical insights into the interactions among ground ice, groundwater, and surface water.

Geophysical exploration methods have proven effective for studying the hydrological effects of permafrost degradation. Resistivity tomography surveys of Arctic lowland bogs and frost-heave depressions have identified open taliks with isotopic evidence supporting the upward transport of subpermafrost water and their contribution to rivers via shallow aquitards. This indicates connectivity between subpermafrost, suprapermafrost, and surface water (Tananaev et al., 2022). In the Upper Aguanegra Basin of Argentina, a rock physics four-phase model based on complementary resistivity tomography and seismic refraction tomography demonstrated that the active layer and ice-rich permafrost control the accumulation and flow paths of shallow groundwater. The regulation of inter-annual runoff in arid mountain basins occurs through water storage and release mechanisms (Halla et al., 2020). Analysis of 52 electrical and 24 seismic refraction profiles in the Andes revealed that ice-rich permafrost is not confined to rock glaciers but also exists on non-rock glacier slopes, where fissure and excess ice are observed (Hilbich et al., 2022). This suggests that the hydrological effects of mountain permafrost degradation

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may have been significantly underestimated. Building on these findings, upscaling methods based on permafrost distribution models and geophysical data have been employed to quantify ground ice on a regional scale, providing a robust framework for estimating the total ground ice volume (Mathys et al., 2022). In the Beiluhe region of the Tibetan Plateau, widespread retrogressive thaw slumps reflect ground ice melt, whereas changes in high ponding depression water turbidity indicate hydrological connections between the melted ground ice and thaw ponds (Niu et al., 2023). The spatial variability of permafrost thaw significantly influences surface and subsurface runoff processes, including water yield capacity and drainage connectivity (Wan et al., 2019). Studies at the southern boundary of the permafrost in northwestern Canada have highlighted the importance of horizontal heat flow in thawing discontinuous permafrost, leading to dramatic land cover changes that alter basin runoff production (e.g. Quinton et al., 2011).

Unlike glaciers, which are directly influenced by atmospheric conditions, permafrost and ground ice exhibit more complex hydrological changes owing to variations in surface sediment composition, vegetation cover, and shallow groundwater flow. These factors influence the heat transfer and timing of hydrological responses. Although the impact of permafrost on flow pathways has been extensively studied in lowland areas, research in mountainous regions remains limited, and contributions of permafrost degradation and ground ice melt to runoff in mountainous areas remain poorly understood. Mountain permafrost, particularly rock glaciers, is often regarded as a frozen reservoir. However, the rate of ground ice melt and its contribution to water resources have rarely been quantified (Arenson et al., 2022).

4.2 Climate change impacts on permafrost hydrology: Increasing baseflow

Significant changes have been observed in the ratio of maximum to minimum monthly runoff (peak-to-baseflow ratio; Qmax/Qmin). Early studies investigating the relationship between permafrost degradation and runoff changes suggest that the intensity of permafrost thaw alone cannot fully explain the observed increases in runoff across large Eurasian rivers. Instead, increased precipitation has been identified as a plausible explanation (McClelland et al., 2004). Further research has confirmed that precipitation increases are the primary driver of runoff changes, whereas permafrost thaw depth primarily affects runoff coefficients and recession processes by altering the soil water storage capacity (Yamazaki et al., 2006; Wang and Zhang, 2016). Using the peak-to-baseflow ratio, subsequent studies have analysed changes in Siberian rivers and found a negative correlation between the mean annual temperature and this ratio, but a positive correlation with the recession coefficient. These findings indicate that changes in the active layer and permafrost conditions have already begun to influence the regional hydrological processes (Ye et al., 2009, 2011; Li et al., 2010). Analysis of annual hydrological processes in basins with varying permafrost coverage revealed that permafrost significantly affected intra-annual runoff distribution. Specifically, a higher permafrost coverage resulted in steeper runoff hydrographs. This highlights the critical role of permafrost coverage in understanding hydrological impacts (Ye et al., 2012).

Significant Increase in Winter Runoff (Baseflow): Winter runoff, also referred to as baseflow, low-flow, or cold-season runoff, has exhibited a clear upward trend. As the active layer thaws, increased infiltration of snowmelt and rainfall during the warm season recharges suprapermafrost water (Song et al., 2022). A portion of this groundwater contributes to surface rivers through subsurface flow and becomes part of the surface water. Studies in China have documented increased winter baseflow in permafrost regions across the northeast (Liu et al., 2003; Lu et al., 2014), northwest (Niu et al., 2011; Qin et al., 2017; Chen et al., 2018; Gao et al., 2018b; Wang et al., 2018b), central Tibetan Plateau (Lan et al., 2015; Gagarin et al., 2022), and surrounding mountainous regions such as the Himalayas and the source of the Yellow River (Zhang et al., 2006; Ma et al., 2020; Song et al., 2020a, 2022; Yang et al., 2023). Similar trends have been observed in Arctic and subarctic regions, including northwestern Canada (Jacques and Sauchyn, 2009), northern Eurasian rivers (Smith et al., 2007), and the Yukon River Basin (Walvoord and Striegl, 2007), where baseflow increases linked to permafrost degradation are widespread (McClelland et al., 2004; Smith et al., 2007; Bense et al., 2009; Jacques and Sauchyn, 2009; Walvoord et al., 2012; Evans et al., 2015; Rogger et al., 2017; Crites et al., 2020). On the northern slopes of the Qilian Mountains, winter runoff (November–March) has increased significantly, with the most pronounced changes occurring in areas with notable permafrost degradation (Gao et al., 2018b). Similar findings from Canada suggest that permafrost influences surface-groundwater interactions, even in low-permeability sediments in the discontinuous permafrost zone near Umiujaq in Nunavik (Québec). Permafrost degradation is expected to increase stream baseflow, particularly in winter (Lemieux et al., 2020). Isotopic studies in the Arctic have also shown that the declining suprapermafrost water tables increase soil storage capacity, enhancing groundwater contributions to rivers during the winter months as seasonal freeze depths decrease (Streletskiy et al., 2015; Crites et al., 2020; Kurylyk and Walvoord, 2021). Research indicates that winter baseflow and its contribution to annual discharge were lower in continuous permafrost catchments than in discontinuous catchments, with general increase from 1970–2016. Analyses and simulations of runoff changes in Russia revealed that reductions in freeze depth and changes in freeze-thaw processes led to significant increases in winter runoff, with increases ranging from 50–120%. Of this increase, 56% was attributed to changes in the freezing front, 38% to thawing processes, and 6% to increased autumn soil moisture (Kalyuzhnyi and Lavrov, 2012). In the source region of the Yellow River, changes in the active-layer thickness and thaw depth were strongly correlated with runoff, with each 1 m increase in the active layer and thaw depth increasing winter runoff by approximately 150 and 400 m^3/s, respectively (Feng, 2020). Observations and simulations suggest that the baseflow increases are driven by factors such as increased suprapermafrost water, active-layer thickening (lowering of the permafrost table), increased deep groundwater flow from unfrozen zones beneath rivers, and enhanced vertical connectivity between recharge areas and valleys (Bense et al., 2009; Ge et al., 2011; Walvoord et al., 2012). Model results further indicate that open lake taliks enhance groundwater flux through suprapermafrost and subpermafrost aquifers, as well as through deep talik systems, by providing vertical flow conduits (Walvoord et al., 2012). Overall, permafrost thinning, active-layer thickening, and rising ground temperatures promote surface water infiltration, increase soil water storage capacity, enhance suprapermafrost water recharge, and boost groundwater flow. Simultaneously, the heat carried by liquid water influences the permafrost, collectively contributing to the increased winter runoff (Chen et al., 2019; Ding et al., 2020a).

Increased winter runoff results in smoother annual hydrographs and extended runoff periods (Lan et al., 2015; Qin et al., 2017; Gao et al., 2018a; Wang et al., 2018b; Chen et al., 2019). Studies of four major rivers flowing into the Arctic found that winter and spring runoff increased, whereas summer runoff decreased, a trend closely linked to earlier snowmelt and permafrost thaw (Li et al., 2010). Research on peat bogs in the Hudson Bay Lowland of northwestern Canada demonstrated that permafrost thaw reduced surface runoff by 47% from 2001–2010 owing to decreased hydraulic gradients, active-layer thickening, and reduced bog area (Quinton and Baltzer, 2013). Although this study did not analyse baseflow changes, active-layer thickening likely increased infiltration into the active layer, reducing surface runoff while potentially increasing baseflow as the water recharged suprapermafrost water and contributed to rivers.

Effect of Permafrost Coverage on Baseflow: The influence of permafrost coverage on baseflow has been highlighted in large-scale comparative studies across the Arctic and Tibetan Plateaus. Basins with high permafrost coverage exhibit higher peak-to-baseflow ratios, whereas those with low coverage have lower ratios, underscoring the importance of permafrost coverage in understanding changes in runoff across the Northern Hemisphere (Song et al., 2020b; Wang et al., 2021a, 2021b). Simulations in the Yukon River Basin demonstrated that decreasing permafrost coverage increases groundwater contributions to rivers, enhances groundwater flux potential, and expands subsurface flow paths, while reducing the contribution of suprapermafrost water to baseflow (Walvoord et al., 2012). Recent studies have indicated that both total discharge and baseflow annual change rates (ΔQ and ΔBF) increase with permafrost coverage, suggesting that runoff increments are more pronounced in basins with high permafrost coverage (Walvoord et al., 2012; Song et al., 2020a). Field investigations on the Tibetan Plateau have also found that increased thaw depths reduce direct runoff ratios, increase groundwater discharge, and slow the recession processes (Wang et al., 2009). Statistical analyses of numerous rivers in the permafrost regions of China have revealed that warming causes higher baseflow and quicker groundwater recession in permafrost-dominated basins (>60% coverage), but has weaker hydrological effects in low-permafrost basins (<20% coverage). This implies that the warming-induced weakening of freezing processes has complex hydrological impacts in Tibetan basins depending on the permafrost coverage (Liu et al., 2020). However, contrasting results suggest that the rate of change in low flows (winter and minimum monthly discharges) is negatively and linearly correlated with permafrost coverage when the coverage is less than 40% of the catchment area, whereas low flows change only slightly when the permafrost coverage exceeds 40% (Wang et al., 2019). This is explained by significant active-layer thickening, which increases low flows in lower permafrost-covered catchments dominated by warm permafrost. In contrast, in higher permafrost-covered catchments with cold permafrost and cold climates, only the permafrost temperature increased (without notable active-layer thickening), resulting in non-significant changes in low flows. Earlier studies also found no substantial relationship between the percentage of permafrost area and changes in annual runoff in the major Eurasian Arctic watersheds (McClelland et al., 2004; Bring et al., 2016).

Divergent Perspectives on Baseflow Variation Mechanisms: Despite the general trend of increasing baseflow due to permafrost degradation, several studies have presented contrasting findings. For example, research on the northern slopes of the Qilian Mountains on the northeastern Tibetan Plateau found a clear decline in winter runoff, whereas annual and seasonal runoff changes were minimal. An analysis of winter runoff, meteorological factors, peak-to-baseflow ratios, recession coefficients, and baseflow indicated that a decline in winter runoff is significantly correlated with permafrost degradation (Gao et al., 2016). Hydrological simulations have also suggested a baseflow reduction in mountainous regions (Gao et al.,

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2022). Even in the subarctic Canadian Shield, increased late autumn rains, rather than permafrost degradation, may drive winter flow enhancement (Spence et al., 2015). Further comparisons of different permafrost types revealed that in catchments underlain by continuous permafrost, active-layer thickening correlates with baseflow increases, whereas in catchments with less extensive permafrost (e.g. discontinuous, sporadic, and isolated), baseflow increases may result from wholesale permafrost loss and vertical talik expansion, enhancing regional groundwater circulation (Evans et al., 2020). These findings underscore the complexity of permafrost impacts on runoff, which depends on surface conditions, active-layer composition and lithology, permafrost thermal state, climate response, and topography, among other factors. Thus, many questions remain unanswered (Adam and Lettenmaier, 2008; Andresen et al., 2020; Arenson et al., 2022; Koch et al., 2022).

4.3 Impact of climate change on hydrology in permafrost regions: Increasing discharge and recharge to surface runoff

In recent decades, groundwater discharge into rivers has increased across the circumpolar region and Tibetan Plateau, which is largely attributed to permafrost thaw (Smith et al., 2007; Walvoord and Striegl, 2007; Jacques and Sauchyn, 2009; O'Donnell et al., 2012; Walvoord et al., 2012; Lindborg et al., 2013; Evans et al., 2015; Wang et al., 2018d, 2024; Wan et al., 2019; Jiang, 2020; Song et al., 2020a; Sun et al., 2020; Ma et al., 2020, 2021). The degradation of permafrost alters landforms and subsurface hydraulic properties, with active-layer deepening enabling water to infiltrate and circulate more freely and deeply (Vonk et al., 2019). Activated groundwater systems can provide new conduits for flushing Arctic basins and transporting nutrients to basin outlets (Kurylyk & Walvoord, 2021). Research in the source region of the Yellow River indicates that permafrost degradation and active-layer deepening have led to a decline in the suprapermafrost water table, resulting in a reduction in the area of wetlands and lakes. This has introduced the concept of the maximum suprapermafrost groundwater table depth necessary to maintain the ecological security in permafrost regions, defined as the minimum depth of the groundwater table required to sustain the normal growth of alpine grassland vegetation (Jin et al., 2022b). This establishes a critical relationship between permafrost degradation, changes in suprapermafrost groundwater levels, and the safety of alpine vegetation. In the Arctic, surface waters in continuous permafrost regions are influenced by short flow paths and shallow suprapermafrost aquifers, which are highly sensitive to climatic changes. Continued warming and permafrost thaw may promote the deepening of shallow subsurface aquifers and formation of shallow taliks, potentially enhancing the resilience of Arctic freshwater ecosystems (Koch et al., 2024).

Because of observational challenges, research on the impact of permafrost thaw on the recharge of subsurface runoff from the active layer remains limited. However, recent studies employing isotopic and modelling approaches have provided preliminary insights into this issue. For example, research conducted in the upper reaches of the Heihe River in the Qilian Mountains revealed that permafrost thaw plays a significant role in the runoff of inland river basins, with thaw-induced runoff contributing approximately 20% of the mountain outflow (Li et al., 2016). This finding suggests that recharge from permafrost thaw exceeds that from glacial meltwater despite the considerable uncertainties associated with isotopic methods. These results underscore the non-negligible hydrological impact of permafrost change in mountainous regions, particularly

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in basins with low glacial coverage. Studies in the source region of the Yellow River have shown that the ice content in permafrost at depths of 3–10 m is 0.31 m³/m³, with higher ice concentrations near the permafrost table (Wang et al., 2018a). Consequently, the thawing of the permafrost table releases a substantial volume of solid water. Both modelling and isotopic analyses indicate that permafrost thaw significantly alters surface and subsurface runoff processes and influences groundwater connectivity and subsurface runoff volume (Lindborg et al., 2013; Wan et al., 2019; Jiang, 2020; Sun et al., 2020; Ma et al., 2021b). For example, isotopic and electrical conductivity-based runoff partitioning in an experimental watershed in the Yellow River source region demonstrated that meltwater from ground ice contributes 13–17% to surface runoff (Yang et al., 2019a). Furthermore, analyses using ^{222}Rn and isotopic methods have highlighted the significant and complex effects of ongoing permafrost degradation on surface and groundwater runoff processes (Wan et al., 2019; Jiang, 2020). Research on runoff changes in the main stem and four tributaries of the Yellow River source region indicates that the permafrost thinning rate in the basin above the Huangheyan hydrological station is 5.6 mm/year, with the released water accounting for 14.4% of the annual runoff at the station. Above the Tangnaihai hydrological section, permafrost meltwater contributes 4.9% of the runoff (Ma et al., 2020). Similarly, in the Yarlung Zangbo River region, estimated permafrost degradation has led to a decrease of ~0.65 km³/year in surface runoff and an increase of ~0.35 km³/year in baseflow, with ground ice melt contributing ~0.25% to the annual streamflow from 2001 to 2022 (Fan et al., 2024). Walvoord and Striegl (2007) documented an annual increase of 0.7–0.9% in groundwater contribution to streamflow (baseflow) over the past 30 years in the Yukong River Basin (Alaska and Canada), likely due to basin-wide permafrost thaw and subsequent changes in watershed hydrology. In the Arctic Kuparuk River, influenced by the expansion of riverbed thaw bulbs and floodplain permafrost degradation, streamflow occurred earlier, and the mean annual river discharge has increased by 35% since the 1970s, accompanied by the emergence of new permanent and seasonal water bodies (Zheng et al., 2019). An analysis of five permafrost rivers in the Eurasian Arctic and Tibetan Plateau revealed that the relative contribution of suprapermafrost groundwater exhibited a significant positive correlation with precipitation and permafrost area. Air temperature has both positive and negative effects on suprapermafrost groundwater discharge, leading to either increasing or falling trends (Wang et al., 2024). The modelling results further indicate that permafrost degradation can increase surface runoff, baseflow, and subsurface runoff, with the magnitude of change being proportional to the permafrost coverage in the basin. Surface runoff, baseflow, and groundwater levels are far more sensitive to permafrost degradation than vadose zone soil moisture, interflow, and subsurface runoff (Sun et al., 2020; Ahmed et al., 2022). Simulations in permafrost forest regions demonstrate that from the forest harvesting to stability period, the combined impact of forest harvesting and permafrost thaw on runoff increase (+47.0 mm) far exceeds that of climate change (+20.2 mm). Conversely, between the forest stability and recovery periods, the impact of forest and permafrost changes on runoff reduction (−38.0 mm) is significantly greater than that of climate change (−22.2 mm) (Duan et al., 2017).

Preliminary results indicate that a substantial volume of groundwater may be stored within intra-permafrost talik layers (Yoshikawa et al., 2006). The talik permeability is a critical parameter that influences aquifer systems in cold permafrost regions. Yoshikawa et al. (2006) identified four distinct flow types associated with perennial intrapermafrost groundwater: (1)

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sub-alas talik network flow in sandy sediments, (2) relict stream talik flow, (3) relict aquifer flow systems in glaciated areas, and (4) limestone-related bedrock-controlled flow systems. Each flow pathway plays a crucial role in the formation of aufeis and springs in permafrost-dominated watersheds (Yoshikawa et al., 2006). In addition to talik dynamics, the degradation of ice wedges in warming permafrost regions has been shown to significantly alter the water balance and increase runoff (Liljedahl et al., 2016). In recent decades, the thawing of ice wedge tops and decimetre-scale ground subsidence have become widespread phenomena in the Arctic. Hydrological modelling suggests that ice-wedge degradation can substantially modify the water balance of the lowland tundra by reducing inundation and enhancing runoff. Ice-wedge degradation and its associated hydrological impacts are expected to expand and intensify rapidly with ongoing permafrost degradation (Liljedahl et al., 2016).

Another significant manifestation of permafrost changes in hydrological processes is their long-term regulatory effects on runoff. As previously discussed, variations in permafrost coverage within basins can substantially alter intraannual runoff processes, highlighting the regulatory role of permafrost. Research on the hydrological impacts of alpine permafrost suggests that its disappearance of alpine permafrost reduces flood peaks and increases runoff during recession periods (Rogger et al., 2017). Permafrost degradation and active-layer thickening not only enhance deep infiltration and increase deep interflow but also expand subsurface water storage capacity, leading to increased baseflow. This is reflected in the increased winter runoff and slower recession curve in autumn, resulting in reduced seasonal variability in stream discharge. These changes effectively regulate intra-annual and inter-annual runoff distributions (Ye et al., 2009; Walvoord et al., 2012; Rogger et al., 2017; Chen et al., 2019; Ding et al., 2020b; Halla et al., 2020; Hiyama et al., 2021a, 2021b; Gagarin et al., 2022; Hilbich et al., 2022; Tananaev and Lotsari, 2022). However, as the permafrost table thaws and the active layer deepens, the freezing depth of the soil decreases, creating additional space for the migration and transformation of soil moisture. Consequently, the soil freezing depth plays a critical role in changes in winter runoff (Liu et al., 2003; Kalyuzhnyi and Lavrov, 2012, 2016, 2017). Furthermore, the gradual melting of substantial ground ice stored within the permafrost slowly replenishes river runoff, providing an effective multiyear regulation of streamflow. Despite these insights, quantitative studies of the contribution of permafrost thaw to runoff recharge are limited. Although results have been obtained through modelling and isotopic methods (Karra et al., 2013; Painter et al., 2013; Ding et al., 2017, 2020a; Li et al., 2020; Song et al., 2020b; Sun et al., 2020), these findings often lack robust validation, limiting their reliability.

Despite the considerable uncertainties in the aforementioned studies, they provided compelling evidence of the impact of permafrost degradation on river runoff recharge. These studies collectively demonstrate that permafrost degradation influences the subsurface runoff to varying degrees. This influence is most prominently observed in the direct recharge of rivers through permafrost degradation, with the recharge volume being non-negligible and reaching significant levels in certain basins. Notably, recharge from permafrost degradation to surface and subsurface runoff is long-term, continuous, and relatively stable. Its significance extends beyond the volume of recharge, encompassing its critical role in regulating hydrological processes at seasonal, annual, multiyear, and long-term scales. However, research on this aspect remains limited and represents a key area for future investigation.

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5 Research trends and existing issues

Under the persistent influence of climate warming, permafrost changes are intensifying, and their impacts on hydrological processes are becoming increasingly pronounced. Research in this field is rapidly expanding. Based on the progress outlined above, the following trends and issues have emerged:

5.1 Long-term observations and new methodologies as the foundation for understanding permafrost hydrology

Field observations serve as the cornerstone of permafrost hydrological research. However, there is a notable lack of comprehensive, interdisciplinary observational systems that integrate permafrost, hydrology, hydrogeology, and ecology. The importance of field observations is self-evident because reliable results for mechanistic understanding, process analysis, model simulation, statistical analysis, remote sensing data interpretation, and isotopic methods ultimately depend on robust observational data. Although global permafrost monitoring, and ecological and hydrological observation networks exist, high-altitude regions present significant observational challenges. This has resulted in sparse or non-existent coverage in these critical areas. Furthermore, existing observation sites are often department-specific or focus on isolated elements and lack the integrated, interdisciplinary systems necessary to address complex scientific questions.

Isotopic methods and geophysical exploration techniques have become indispensable tools for analysing the relationship between permafrost and hydrology. However, improving their reliability and reducing uncertainty remain key challenges for future research. Isotopic and geophysical methods play pivotal roles in quantifying ground-ice volume, estimating permafrost meltwater recharge, tracing water sources, and identifying runoff components. Furthermore, the results derived from these methods often lack direct observational validation, raising concerns regarding their reliability and uncertainty. To address these limitations, multimethod approaches, such as combining isotopic analysis with modelling, can provide mutual validation and enhance the robustness of the findings. Additionally, as permafrost degradation increases groundwater recharge into rivers, the biogeochemical composition of river water undergoes significant changes. Leveraging biogeochemical indicators to identify the connections between permafrost thaw and changes in river runoff may offer a promising avenue for future research. For example, studies have demonstrated that dissolved organic matter (DOM) concentrations are highest in stream-draining watersheds with extensive underlying permafrost, whereas nitrate concentrations are highest in stream-draining catchments with less permafrost (Jones, 2014). This suggests that the DOM concentration could serve as a potential indicator of permafrost-related hydrological impacts, providing a novel pathway for future investigations.

Modelling has become a widely used tool for studying the hydrological impacts of permafrost change. However, significant challenges remain in parameter acquisition, process understanding, surface-groundwater coupling, and the validation of the results. Various models incorporating permafrost thermal-hydrological processes have emerged as effective tools for permafrost hydrology research and are now widely applied, representing the mainstream approach. Complexity in coupled heat-water equations, parametrization uncertainties, and data deficits for model validation are the three key challenges in permafrost change simulation. Current models exhibit high sensitivity to the parametrization of unfrozen water content (w_u); however, observational data for w_u remain scarce and challenging to upscale (Sun et al., 2025). For instance, in the Mackenzie Basin model, discrepancies in w_u schemes induce ±25% deviations in simulated summer peak flows (Elshamy et al., 2025). Abrupt processes such as thermokarst development are largely absent in existing models, yet satellite observations indicate they contribute to over 40% of land subsidence in the Yangtze River headwaters. While active-layer thickening significantly impacts baseflow by altering groundwater pathways, resolving these processes necessitates coupled surface-subsurface hydrological models—currently constrained by computational demands. Theoretically, hydrological changes and permafrost thawing under the influence of climate change are causally linked. However, because of the limited understanding of hydrogeological processes in the permafrost and active layer, scarcity of historic observational data, and necessary simplifications in model structures and processes for cryosphere hydrogeological modelling, process-based simulations often face substantial limitations (Kurylyk and Walvoord, 2021; Abdelhamed et al., 2022). Furthermore, the heterogeneity of permafrost and variability in thawing patterns and rates make the relationship between different permafrost thawing modes and hydrological changes highly context-dependent (Walvoord and Kurylyk, 2016). Recent advancements in permafrost hydrogeological modelling have led to the development of several mainstream groundwater models, such as SUTRA, FEFLOW, and HYDRUS, which offer advanced capabilities for simulating processes in aquifers experiencing dynamic freeze-thaw cycles (Kurylyk and Walvoord, 2021).

Recent methodological innovations are fundamentally reshaping observational and predictive capabilities in permafrost hydrology. Machine learning techniques now enable high-resolution parameterization of previously intractable processes, particularly through deep learning architectures applied to remote sensing data. Zwieback et al. (2025) proposed an InSAR-based approach for estimating ground ice near the permafrost table in sparsely vegetated terrain underlain by continuous permafrost. Concurrently, microfluidic experimentation has emerged as a transformative laboratory paradigm, with etched silicon chips replicating cryogenic pore networks at micrometer scales. The microcosms directly visualize ice-lens growth dynamics during freeze-thaw cycles. When coupled with X-ray microtomography, this approach has revealed hysteresis in hydraulic conductivity-ice saturation relationships that violate classical frozen soil models, explaining field observations of delayed runoff response after thaw events (Mirzaei et al., 2025).

Conceptual breakthroughs are similarly redefining system understanding, most notably through the Thermokarst-Driven Hydrological Restructuring hypothesis formalized by Jorgenson et al. (2022). This paradigm posits that thermokarst initiation triggers self-reinforcing feedback loops: initial subsidence creates depressions that enhance surface water pooling → ponded water accelerates lateral thaw through convective heat transfer → expanding taliks integrate previously isolated aquifers → groundwater discharge further destabilizes adjacent permafrost. Such restructuring explains the nonlinear acceleration of watershed-scale drainage density increases observed across the Arctic, where some regions exhibit >400% growth in thermokarst channels within a single decade (Farquharson et al., 2023). Complementing this, the theory of Non-Stationary Hydrological Connectivity (Connon et al., 2022) provides a mechanistic framework for threshold behaviors in cold-regions catchments. It demonstrates that subsurface flowpath activation requires simultaneous satisfaction of three conditions: (i) ice content below critical storage capacity (typically <40% by volume), (ii) hydraulic gradient exceeding cohesive strength of frozen sediments, and (iii) presence of through-going taliks. This triad explains the episodic "switch-like" release of stored meltwater documented in instrumented polygonal tundra, where isolated wetlands abruptly integrate into basin-scale drainage networks following sustained warming anomalies (Liljedahl et al., 2016).

These advances collectively establish a new Smart Simulation Paradigm integrating data-driven and physics-based approaches. Hybrid models embedding machine-learned parameterizations within process-based frameworks (e.g., CNN-informed subsurface properties in CryoGrid) now simulate permafrost-hydrological feedbacks faster than conventional models while maintaining most physical consistency (Westermann et al., 2022; Wang et al., 2023). Crucially, they enable probabilistic projections of tipping points – such as the 1.7°C regional warming threshold predicted to trigger irreversible drainage reorganization in ice-rich Siberian lowlands (Nitzbon et al., 2020). As these methodologies mature, they promise to resolve the persistent scale-disconnect between pore-scale cryohydrogeological processes and landscape-scale impacts that has long constrained predictive capability in thawing landscapes.

Critical knowledge gaps persist in quantifying ground ice dynamics, winter hydrological processes, and cross-scale modeling, demanding targeted methodological innovations to advance predictive capability in permafrost hydrology. The spatiotemporal heterogeneity of ground ice content—particularly the three-dimensional distribution of massive ice wedges and pore ice—remains poorly resolved at meter-to-kilometer scales (Kizyakov et al., 2024), limiting our ability to parameterize thaw-induced subsidence and hydrologic reconfiguration (Aas et al, 2018; Langford et al, 2020). This gap necessitates joint inversion techniques combining time-lapse electrical resistivity tomography (ERT) with induced polarization (IP) to simultaneously map ice saturation variability and structural deformation at submeter vertical resolution (Revil et al., 2015). Concurrently, the mechanisms governing snowmelt migration through frozen soils represent a fundamental process uncertainty, as current models fail to capture preferential flowpaths along cryostructures during freeze-thaw transitions (Mohammed et al., 2021). Tritium isotope tracing coupled with ^{222}Rn offers transformative potential to quantify meltwater velocities and residence times within seasonally frozen active layers, resolving critical thresholds where ice barriers redirect supraglacial flowpaths (Wan et al., 2019). Most critically, the plot-to-catchment scaling bottleneck continues to impede regional projections, where point-scale process understanding (e.g., cryohydrogeological interactions within instrumented polygons) fails to inform watershed-level responses due to nonlinear emergent behaviors (van Meerveld, 2024). Implementing physics-informed deep learning architectures—particularly convolutional long short-term memory (ConvLSTM) networks that assimilate drone LiDAR, ERT, and borehole data—can bridge this scale discontinuity through learned spatial embedding of cryostratigraphic complexity. Addressing these prioritized gaps through coordinated deployment of ERT/IP fusion, isotope-enabled field experiments, and AI-driven downscaling will substantially reduce the uncertainty in permafrost hydrological feedback projections identified in recent model intercomparisons (Tang, 2025). The quantitative assessment of the hydrological and environmental consequences of permafrost change is significantly constrained by methodological heterogeneity, inconsistent reporting practices, and limited data accessibility. Addressing these challenges necessitates the standardization of methodologies and a concerted effort by the research community to establish curated, open-access databases, which are imperative for enabling robust meta-analyses in the future.

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5.2 Integrated surface-subsurface research as the path to systematically and accurately revealing permafrost hydrological change mechanisms and impacts

Research on permafrost hydrology has primarily focused on either the hydrological effects of surface or active layer freeze-thaw processes or the contribution of permafrost degradation to runoff. However, there is a notable lack of integrated research examining the impact of permafrost change on hydrological processes from a comprehensive surface-active layer-permafrost (SAP) perspective (Fig. 4). Research on the relationship between permafrost changes and hydrological processes spans a wide range of topics, including surface freeze-thaw cycles, active layer dynamics, and the impacts of permafrost degradation on subsurface and surface runoff. Over the past decade, the widespread application of isotopic and geophysical methods, coupled with advancements in modelling and remote sensing, has significantly advanced the field of permafrost hydrology. Nevertheless, most studies have focused on isolated aspects of the surface, active layer, or permafrost hydrology rather than adopting a holistic approach.

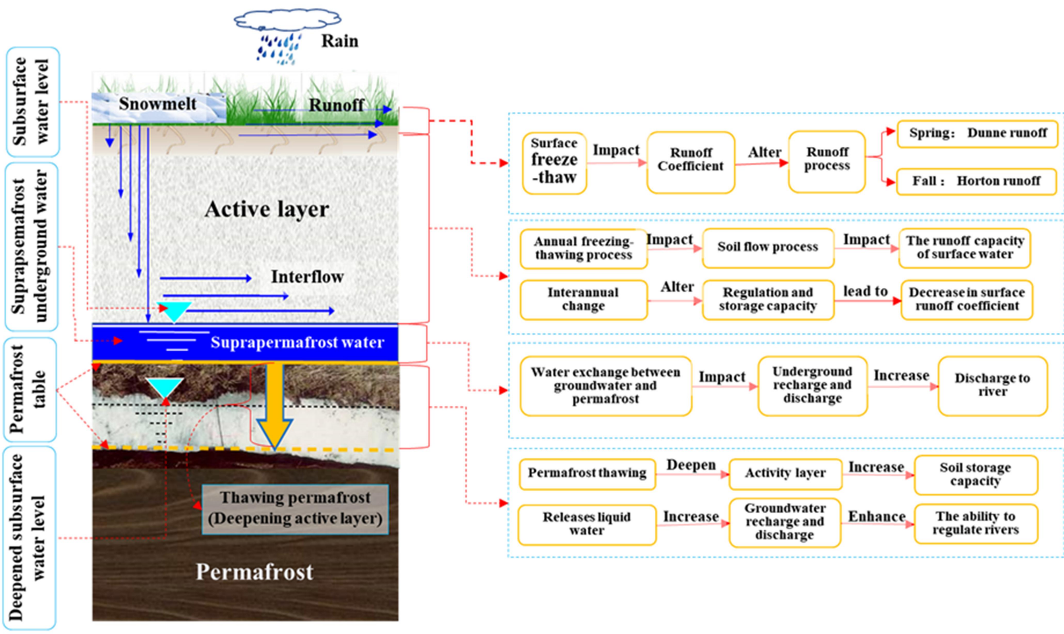

Figure 4: Schematic diagram of the Surface-Active layer-Permafrost (SAP) integrated hydrological system.

In surface hydrology, the annual freeze-thaw cycle of the active layer significantly influences snowmelt and rainfall runoff processes, with the most pronounced effects occurring during the spring thaw and autumn freeze periods. However, the full coupling relationship between active-layer thawing and surface hydrological processes remains poorly understood.

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On a multi-year timescale, as permafrost thaws and the active layer deepens, previously stable surface hydrological processes may undergo substantial or even abrupt changes. Whether a threshold active-layer depth exists to trigger such changes remains unknown. In terms of active-layer hydrological processes, the formation of subsurface runoff and its contribution to river recharge are poorly understood. Similarly, the transformation between liquid and solid water in the suprapermafrost layer remains a critical knowledge gap. Regarding the hydrological impacts of permafrost degradation, the contribution of permafrost thaw to subsurface runoff and river recharge has attracted increasing attention. However, research in this area is still in its early stages, with significant uncertainties in both the hydrological processes and quantitative assessments.

Although research on permafrost hydrology has expanded significantly, integrated studies from a SAP system perspective under changing environmental conditions remain limited. In permafrost regions, surface water, suprapermafrost groundwater, and water released from permafrost degradation are interconnected and mutually influential. Understanding these dynamic hydrological processes requires a comprehensive approach based on water and heat balance theory. This approach should examine the impacts of freeze-thaw cycles on surface runoff, active layer changes on subsurface runoff, and permafrost degradation on river recharge. The active layer serves as a critical link in the SAP hydrological chain. Future research should investigate these changes and their hydrological effects to determine the mechanisms and interactions within the SAP system. Such efforts can provide a more holistic understanding of permafrost hydrology and its response to environmental change.

In summary, the hydrological impacts of permafrost changes span three spatial dimensions: (1) surface hydrological processes, (2) suprapermafrost hydrological processes, and (3) the thermal-hydrological interactions between the active layer and permafrost. Temporally, these impacts encompass intra-annual hydrological processes driven by freeze-thaw cycles and multi-year hydrological changes resulting from permafrost degradation and active layer thickening (Fig. 4). Whether examined from a spatially or temporally, changes in the surface and subsurface hydrological processes induced by permafrost dynamics form an integrated hydrological system. Therefore, it is essential to study permafrost hydrology from a systemic perspective by recognising the interconnected and interdependent nature of these processes.

5.3 Ecological and environmental effects of permafrost hydrological changes as a key focus area for future research

Permafrost degradation triggers profound and far-reaching hydrological changes, with significant ecological and environmental implications. One of the most critical projected consequences of permafrost thaw is the transition of the Arctic terrestrial freshwater system from surface-water-dominated to groundwater-dominated (Frey and McClelland, 2009). On the Tibetan Plateau, permafrost degradation can disrupt the hydrological-ecological balance between suprapermafrost groundwater and alpine vegetation. This raises the question of the maximum suprapermafrost groundwater table depth necessary to maintain ecological security in permafrost regions or, specifically, the minimum groundwater depth required to sustain alpine grassland vegetation (Jin et al., 2022b). Accompanying this transition, mineral-rich groundwater may become a significant contributor to the streamflow, complementing the currently dominant contribution of mineral-poor surface waters (Frey and McClelland, 2009). These shifts highlight the need for future research focusing on the ecological and

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environmental effects of permafrost hydrological changes, particularly in the context of climate warming and its cascading impacts on freshwater systems and ecosystems.

Permafrost hydrology is intricately linked to the carbon and nitrogen cycles, vegetation dynamics, aquatic ecosystems, and chemical transport. Changes in permafrost hydrology not only alter water transformation and cycling but also release previously "frozen" nutrients and chemicals, thereby influencing the carbon and nitrogen cycles, terrestrial and aquatic ecosystems, river sediment dynamics, and chemical processes. These changes are primarily driven by shifts in soil moisture distribution, suprapermafrost groundwater recharge, subsurface runoff, and groundwater levels, which subsequently affect surface landscapes, vegetation, carbon and nitrogen cycles, and the transport of chemicals and nutrients (Frey and McClelland, 2009; O'Donnell et al., 2012, 2019, 2024; Drake et al., 2018; Gandois et al., 2019; Liljedahl et al., 2020; Hirst et al., 2022; Mann et al., 2022; Skovsholt et al., 2020; Rowland, 2023). Consequently, the ecological and environmental effects driven by changes in the permafrost hydrology represent a critical area for future research with far-reaching implications. These effects are closely tied to water, ecological, climate, and environmental security, making them a key focus that requires significant attention.

Author contribution

Jia Qin and Guangxi Ding conceptualized the study and outlines of the article. Guangxi Ding prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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