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Tracing Subsurface Hydrological Reorganization in Cryosphere-Related Hazard Systems Using Isotope Hydrology

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Abstract

Cryosphere-related hazard assessment increasingly integrates remote sensing, geomorphological analysis, geophysical surveys and hydrodynamic modelling. Nevertheless, the processes controlling how changes at the surface affect groundwater storage, the movement of water below the surface, and the connections between surface water and groundwater remain poorly understood. Advances in isotope techniques have greatly improved our ability to identify and quantify subsurface hydrological processes (e.g., meltwater routing, storage, and mixing) across a range of glacial and periglacial settings, offering a way to trace subsurface flow paths that surface-based methods cannot detect. However, isotope-based information is not yet included in assessment frameworks. In this paper we show how isotope information can catalyse cryo-hazards diagnostics and support developing predictive systems that consider the hydrological precursors before and after the failure of a system occurs. We propose an isotope-enabled framework for the assessment of hazards related to glacier and ground ice degradation using a multi tracer approach. Two main outputs are presented: (1) a five-phase monitoring framework comprising cryosphere characterization, seasonal baseline establishment, detection of hydrological reorganization, and decision-support and (2) a hazard-specific tracer interpretation matrix linking isotopes and complementary tracers to water sources, flow pathways, storage, residence time, and subsurface reorganization. The framework is explicitly diagnostic rather than predictive: isotope and hydrochemical anomalies are interpreted as evidence that a system has shifted from expected seasonal behaviour toward a reorganized and potentially more sensitive hydrological state, potentially indicating a change in factors determining the stability of frozen systems. Used alongside hydrometeorological, geomorphic, geophysical, and remote-sensing observations, the approach provides a practical basis for integrating subsurface-sensitive information into hazard assessment. It is intended for the scientific community and support the design of early-warning systems.

1. Introduction

Cryosphere change is reshaping cryosphere mountain ecosystems creating dynamic conditions for the emergence, interaction, and propagation of hazards (Haeberli et al, 2015; Deline et al., 2021; Shugar et al., 2020; Zhang et al., 2024a; Zhang et al., 2024b). As glaciers thin and retreat, formerly ice-supported valley walls may become exposed, proglacial areas commonly expand, and new lakes can form where local topographic and geomorphic conditions favour water impoundment, including behind moraines, bedrock thresholds, dead ice, and debris complexes (Harrison et al., 2017). These changing environments are often characterized by rapidly changing drainage networks (Shugar et al., 2020; Deline et al., 2021). These variations do not only reflect the loss of glacier and ground ice volumes; they indicate a broader reorganization of mountain hydrological and geomorphological systems, with consequences for water resources, downstream exposure, and natural hazards (Haeberli et al, 2017; Zhang et al., 2024b; Veh et al., 2025).

Cryosphere-related hazards pose significant threats to mountain communities, causing substantial loss of life, destruction of infrastructure, and economic disruption. Glacier outburst floods alone have been

associated with more than 12,000 recorded fatalities worldwide (Carrivick and Tweed, 2016). A global inventory of 3,151 glacial lake outburst floods (GLOFs) compiled by Lützow et al. (2023) identified 404 events with reported damage, including destruction of bridges, damage to roads and buildings, agricultural losses, and disruption of essential infrastructure such as hydropower facilities and water supply networks. These impacts can have particularly severe consequences in remote mountain regions, where communities depend on limited transportation networks, agricultural activities, and critical infrastructure. The scale of potential future impacts is considerable, with approximately 15 million people worldwide exposed to possible GLOF impacts, particularly in High Mountain Asia and the Andes (Taylor et al., 2023). Despite these substantial human and economic consequences, important gaps remain in the detection and characterization of the hydrological processes that contribute to the development of cryosphere-related hazards.

The assessment approaches of major cryosphere-related hazard listed and defined in **Table S1** have advanced over the past two decades, particularly through the increasing use of remote sensing techniques and improvements in the spatial and temporal resolution of remote sensing products. However, the remote sensing techniques are effective at detecting visible changes and characterising surface processes, but they generally provide only indirect constraints on internal hydrological reorganization (Miles et al., 2020; Racoviteanu et al., 2021). In many glacierized basins, processes relevant to hydrological evolution and hazard development occur below the surface or within mixed ice–debris systems. This includes, across different cryosphere settings, groundwater leakage from moraine-dammed lakes, evolution of subglacial or englacial drainage, thawing of buried ice, development of subsurface conduits through moraines, changing water residence times, and progressive saturation of unstable slopes (Hansen et al., 2020; Giacaman and Schoof, 2023; Bearzot et al., 2023). Such processes can influence lake level, groundwater level, dam stability, slope stability, yet they often remain undetected by remote sensing until a failure or rapid hydrological response has already occurred (Lala et al., 2017; Mergili et al., 2019; Sattar et al., 2022). Past events illustrate how relatively localized or apparently limited changes can initiate much larger cascading process chains: the 2016 outburst of the small Gongbatongsha Lake in the Himalaya was triggered by slope failure and rapidly amplified through sediment entrainment into a large transboundary debris-laden flood (Sattar et al., 2022), while in 1941 outburst of Lake Palcacocha in Peru propagated downstream and caused the complete drainage of Lake Jircacocha before devastating Huaraz (Mergili et al., 2020). Similarly, process-chain modelling at Imja Tsho in Nepal illustrates how an avalanche entering a glacial lake can generate impulse waves, moraine erosion, and downstream flooding, even where the initial perturbation is spatially restricted (Lala et al., 2018). A moraine-dammed lake may appear stable in terms of surface area, while internal seepage or piping progressively modifies dam structure and sediment strength (Begam et al., 2018). The catastrophic event along the Nepal–China border on 26 August 2026 provides a compelling example of this challenge. Preliminary assessments suggest that a large slope failure involving glacier ice and underlying rock in the upper Lhende catchment evolved rapidly into an rock-ice avalanche, mobilizing water, sediment and boulders and producing a destructive flood that propagated downstream through the Lhende Khola–Bhote Koshi–Trishuli river system (Xu, 2026; Tsou et al., 2026). Temporary river

blockage and the subsequent formation and evolution of debris-dammed water bodies further introduced the potential for secondary outburst floods. The event illustratess how changes in hydrological connectivity within cryosphere–river systems can contribute to cascading and compound hazards. Together, these past events highlight the potential limitations of relying solely on surface observations to anticipate such events, particularly where subsurface water storage and flow pathways may play an important role. This underscores the value of approaches that can complement surface monitoring by providing information on changes in water sources, flow pathways, and storage within the catchment.

Isotope hydrology can offer a direct way to investigate some of the subsurface cryosphere–hydrology linkages (Zhou et al., 2014; Miller et al., 2021; Wanner et al., 2023). Stable isotopes in the water molecule based on their ratios, such as $\delta^{2}H$ and $\delta^{18}O$, along with complementary geochemical indicators, can in many mountain catchments help distinguish precipitation, snowmelt, glacier melt, lake water, and groundwater (Vystavna et al., 2026) particularly when combined with hydrological and geomorphic observations (Bantcev et al., 2024; Müller et al., 2025; Charonnat et al., 2025). Recent applications showed that isotope hydrology can complement remote sensing and modelling (He et al., 2019) by resolving processes that are not directly visible from above. Despite this potential, isotope hydrology has not yet been systematically integrated into cryosphere-related hazard assessment frameworks. This paper addresses this gap by proposing a conceptual framework for detecting hydrological reorganization in glacier and permafrost -related hazard settings. The objectives are to: **(i) identify key gaps in the assessment of hydrologically mediated cryospheric hazard assessment (ii) propose a phased monitoring and decision-support framework for detecting and interpreting hydrological reorganization (iii) identify hazard-specific applications of isotopes and hydrochemical tracers.**

2. Methodology

2.1. Scientific basis and expert consultation

This study was developed through a synthesis of existing scientific knowledge and expert discussions conducted during an International Atomic Energy Agency (IAEA) consultancy meeting on the “Development of an Isotope-Enabled Method for the Assessment of Glacier Hazards and Hydroclimate Archive Loss in Glacier-fed Basins”. The meeting brought together specialists in isotope hydrology, glacier hydrology, cryosphere-related hazards, permafrost science, remote sensing, hydrological modelling, and risk assessment. The objective was to evaluate how isotope and hydrochemical tracers could improve the characterization of subsurface hydrological processes associated with the development of cryosphere-related hazards and complement existing monitoring and assessment approaches. Particular attention was given to processes that are difficult to observe using conventional surface-based methods, including changes in meltwater contributions, subglacial and englacial drainage, groundwater connectivity, moraine seepage, thawing of ground ice, and subsurface water storage. Expert discussions also addressed the practical requirements for integrating isotope hydrology into

monitoring programmes and the potential contribution of tracer-based observations to hazard assessment and decision support.

2.2. Assembly and screening of the scientific evidence

The scientific evidence base was developed from published studies addressing cryosphere-related hazards, associated hydrological processes, and applications of isotope and hydrochemical tracers in glacierized and permafrost-affected environments. The literature synthesis focused on three main areas: (i) the mechanisms and hydrological conditions associated with glacier instability, glacial lake outburst floods, permafrost-related slope failures, and cascading hazards; (ii) existing approaches for hazard identification, monitoring, and assessment, including remote sensing, geomorphological investigations, geophysics, and hydrological modelling; and (iii) applications of isotope hydrology for identifying water sources, subsurface flow pathways, groundwater contributions, mixing processes, and water storage. Studies were examined for their relevance to understanding the relationships between hydrological processes and cryosphere-related hazards, with particular attention to evidence of changes in subsurface drainage, water sources, and hydrological connectivity. The synthesis distinguished between documented applications of isotope tracers, interpretations supported by complementary hydrological observations, and potential applications that have not yet been systematically evaluated in hazard assessment. The review was intended as a targeted scientific synthesis rather than a systematic review or meta-analysis. Consequently, the objective was not to provide an exhaustive inventory of published studies, but to identify established hydrological processes, relevant tracer applications, methodological limitations, and opportunities for integrating isotope hydrology into existing hazard assessment approaches.

2.3. Organization and interpretation of the evidence

The collected evidence was organized according to hazard type, relevant hydrological processes, and the potential contribution of isotope and hydrochemical tracers. For each hazard category, the synthesis considered the hydrological mechanisms potentially influencing system stability, the water sources and flow pathways involved, the monitoring locations where changes might be detected, and the isotope or hydrochemical parameters capable of providing relevant information. Particular attention was given to stable water isotopes ($\delta^{18}O$ and $\delta^{2}H$), tritium (^{3}H), radon-222 (^{222}Rn), strontium isotopes ($^{87}Sr/^{86}Sr$), and complementary hydrochemical parameters, including electrical conductivity and major ions. Their potential applications were evaluated in relation to water-source identification, groundwater–surface water interactions, water residence time, water–rock interaction, and changes in subsurface hydrological connectivity. The synthesis also considered limitations related to overlapping isotopic signatures, seasonal variability, tracer-specific behaviour, and the non-unique interpretation of hydrological anomalies. This distinction was important to avoid interpreting tracer variations as direct evidence of increasing hazard probability without supporting observations. The resulting information was structured into a hazard-specific interpretation matrix linking hazard types, relevant tracers, monitoring targets, and possible hydrological interpretations.

2.4. Development of the isotope-enabled assessment framework

The conceptual framework was developed by integrating the scientific evidence with the technical considerations identified during the expert consultation. Its development followed a process-oriented approach, beginning with the identification of potentially hazardous cryosphere systems and progressing toward the detection and interpretation of subsurface hydrological changes. The framework was organized into five successive phases: (1) characterization of the cryosphere system and identification of relevant hazards; (2) establishment of seasonal isotope and hydrochemical baselines; (3) detection and interpretation of deviations potentially indicating hydrological reorganization; (4) integration of multiple lines of evidence to support hazard assessment and decision-making; and (5) translation of scientific findings into monitoring priorities and resilience measures. The first three phases focus on developing a conceptual hydrological model, characterizing normal seasonal variability, and detecting changes in water sources, storage, flow pathways, and connectivity. The subsequent phases address how these observations may be interpreted alongside hydrometeorological, geomorphological, geophysical, and remote-sensing information to inform hazard assessment and management decisions. The hazard-specific tracer interpretation matrix was developed as a complementary component of the framework, providing a structured connection between individual tracer applications and the hydrological processes relevant to different cryosphere-related hazards. The proposed approach is conceptual and diagnostic rather than predictive. It does not establish universal isotope thresholds for hazard occurrence or provide a validated method for predicting the timing of glacier collapse, glacial lake outburst floods, or slope failures. Instead, it provides a scientific basis for identifying subsurface hydrological changes that may influence system stability and for guiding the future development and evaluation of integrated monitoring strategies.

3. Results and discussion

3.1. Knowledge gaps related to the subsurface hydrological processes

Existing cryosphere-related hazard assessment approaches provide an essential basis for identifying visible instability, exposure, and potential impact pathways, but they only partly resolve the subsurface hydrological processes that may precondition hazard development. Remote sensing has enabled repeated mapping of the glacier retreat and development of glacier lake inventories which include area change, dam geometry, surrounding slope conditions, and downstream flood pathways (Kapitsa et al. 2017; Muneeb et al., 2021, Rawat et al., 2023; Yang et al., 2023; Lützow et al., 2023; Nurakynov et al., 2025). Digital elevation models, optical and radar satellite products, drones, field geomorphological surveys, and historical event inventories now provide the basis for regional to global assessments of glacial lake outburst flood susceptibility (Wilson et al., 2018; Nie et al., 2018; Ahmed et al., 2021; Emmer et al., 2022a; Emmer et al., 2022b; Shrestha et al., 2023; Kroczek & Vilímek, 2024; Colavitto et al., 2024).

GIS-based multi-criteria methods are widely used to screen lakes according to factors such as area, growth rate, distance to glacier fronts, dam type, slope angle, freeboard, potential avalanche source areas, and downstream exposure (Upadhyaya & Rai, 2025). Hydrodynamic models can simulate flood hydrographs, dam-breach scenarios, debris-flow, and inundation zones (Nie et al., 2020; Yang et al., 2023; Jiang et al., 2023; Motschmann et al., 2020; Moreiras et al., 2024).

Hydrogeophysical methods have also significantly improved the characterization of subsurface conditions in glacierized and permafrost-affected environments. Ground-penetrating radar (GPR), surface nuclear magnetic resonance (SNMR), and electrical resistivity tomography (ERT) provide information on subsurface structures, water accumulation, ice distribution, and changes in frozen and unfrozen ground. For example, the combined application of GPR and SNMR at Glacier de Tête Rousse in the French Alps enabled the detection of a subglacial water reservoir estimated at approximately 55,000 m^3, whose elevated water pressure represented a potential outburst-flood hazard (Vincent et al., 2012). Similarly, time-lapse ERT has been successfully applied to monitor permafrost degradation in steep rock walls by detecting changes in electrical resistivity associated with ice and liquid water distribution and seasonal thawing (Krautblatter and Hauck, 2007; Herring et al., 2023). These methods provide valuable spatial information on subsurface conditions and their evolution. However, geophysical measurements alone may not uniquely determine water origins, mixing processes, residence times, or hydrological connectivity. Isotope hydrology can complement these observations by identifying water sources and tracing changes in subsurface flow pathways, thereby providing additional information on the hydrological processes associated with cryosphere-related hazards.

Together, these approaches are indispensable for hazard screening, monitoring design, and disaster-risk reduction. However, they remain primarily focused on surface expression and geomorphic configuration (Magnin et al., 2020; Haeberli et al., 2017; Furian et al., 2021; Carrivick et al., 2022). This limits the capacity to evaluate how subsurface hydrological change may precondition hazards. Isotopes do not directly predict the timing of a glacier collapse, glacial lake outburst flood, rock avalanche, or debris flow, but their value lies in identifying hydrological conditions that may increase hazard susceptibility, such as increasing lake–groundwater connectivity, changing meltwater sources, activation of drainage pathways, increasing contribution of buried-ice melt, prolonged residence times within unstable deposits, or rapid changes in runoff generation during warm or wet periods (Wang et al., 2016; Schubert et al., 2024; Wang et al., 2024a; Delpero et al., 2025). Used in this way, isotope and hydrochemical data can add a subsurface-sensitive diagnostic component to broader hazard assessment workflows.

3.2. Subsurface hydrological controls in Cryosphere-related hazard systems

3.2.1. Glacier collapse, detachment, and ice avalanches

Glacier collapse, detachment, and ice avalanches represent distinct but overlapping modes of glacier instability, differing in slope angle, volume, mechanism, and runout behaviour. These three phenomena

can be viewed as part of a broad spectrum of gravitational glacier failures, ranging from relatively frequent small icefalls to rare large catastrophic detachments involving substantial portions of a glacier (Bashkova et al., 2026). The term glacier collapse is often used in the literature to describe sudden large-scale failure of glacier ice. Depending on the setting, it may refer to the failure of a glacier sector, hanging-glacier fall, or more extensive glacier detachment. Such events have received increasing attention in the context of changing glaciergeometry, thermal conditions and climate-related glacier instability (An et al., 2021; Francese et al., 2025). Glacier collapses can be promoted by anomalous meltwater production, over pressurized englacial or subglacial drainage, crevasse water loading, hydraulic jacking, and basal friction reduction rather than by any single mechanism acting alone (Bondesan & Francese, 2023; Baroni et al., 2026). Retreating and thinning glaciers increasingly develop collapse features such as subglacial cavity roof failures, which are driven by glacier downwasting (Sommer et al., 2020), enhanced energy supply through subglacial conduits, and locally increased basal melt, and have become more frequent in recent decades (Hösli et al., 2025). Indeed, the collapse of the glacier that caused the catastrophic flood in the Lhende catchment in Nepal-China border was preceded by a 450 m retreat of its tongue between 1990 and 2020, resulting in the loss of its buttressing effect on the underlying bedrock slope while permafrost was generally warming and destabilising mountain slopes. Glacier detachment is a rare form of glacier instability in which substantial portions of comparatively low-angle glaciers fail abruptly. Documented events have commonly d glacier surface slopes of approximately 10–20°, and detached volumes ranging from 10^6 to 10^8 m^3 (Kääb et al., 2018; Kääb et al., 2021; Bashkova et al., 2026). Ice avalanches by contrast generally originate from steep glacier fronts or hanging glaciers where slopes exceed r 30°, although some detachments from lower-angle glaciers also transform into ice avalanches during runout (Zhong et al., 2024). In some events, the presence of liquid water, fine-grained sediment, and entrained debris can enhance mobility and favour transitions toward debris-rich mass flows, potentially initiating cascading processes such as river blockage, temporary lake formation, and subsequent outburst flooding (An et al., 2021; Li et al., 2024, Li et al., 2025a; Li et al., 2025b).

3.2.2. Glacial lake outburst floods

Since 1990, the number, area, and volume of glacial lakes have increased worldwide, with particularly strong expansion reported in High Mountain Asia, the Andes, the European Alps, and Alaska (Livingstone et al., 2022; Taylor et al., 2023; Zhang et al., 2024a; Kumar et al., 2024; Veh et al., 2025). Many of these lakes occupy recently deglaciated terrain and are situated below steep glacier fronts, hanging glaciers, degrading permafrost slopes, or unstable lateral moraines (Harrison et al., 2017). Their continued growth has increased the number of potentially hazardous lakes and the exposure of downstream communities and infrastructure to future glacial lake outburst floods (GLOFs), particularly where dams consist of unconsolidated moraine material, buried ice, fractured bedrock, or complex ice-debris mixtures (Erokhin et al., 2018; Zheng et al., 2021; Ahmed et al., 2021; Taylor et al., 2023). However, an increase in glacial lake area and volume does not necessarily translate into an increase in observed GLOF occurrence. At the global scale, there is currently no evidence for a rising frequency of moraine-dammed GLOFs despite ongoing glacier retreat and lake growth (Harrison et al., 2018), and similar conclusions have been

reported for the northern Tien Shan, where no increasing trend in debris-flow activity linked to GLOFs has been observed (Shahgedanova et al., 2024). Nevertheless, rapidly expanding proglacial lakes in regions such as the Himalaya and Tien Shan, the tropical Andes, and the European Alps remain a significant concern because future outburst events could affect increasingly exposed populations, infrastructure, and economically important mountain areas (Emmer et al., 2022; Rawat et al., 2023; Colavitto et al., 2024; Taylor et al., 2023). Some GLOFs occur as part of cascading hazard sequences in which processes such as slope failure or ice avalanches may trigger lake drainage, while sediment entrainment and channel erosion can promote downstream debris-flow development and flooding (Nie et al., 2020; Veh et al., 2025). Outburst initiation mechanisms commonly include dam degradation associated with ice melt, overtopping triggered by mass movements into lakes, and blockage or failure of dam structure (Richardson and Reynolds, 2000). A lake may remain stable for years before being disturbed by an ice avalanche, rockfall, debris flow, moraine failure, rapid snowmelt, intense rainfall, or internal drainage reorganization (Ahmed et al., 2022; Wangchuk et al., 2022).

Beyond changes in lake area and dam geometry, GLOF susceptibility may also depend on the internal hydrological functioning of the lake–dam–aquifer system. Moraine seepage, groundwater leakage, buried-ice melt, and the opening, closure, or reorganization of subsurface drainage pathways can modify dam saturation, internal erosion potential, and lake-level response, potentially before clear surface changes are detectable. Characterizing these processes therefore requires information not only on the amount and location of water, but also on its sources, flow pathways, connectivity, mixing, and storage. Isotope hydrology may provide complementary information on these processes. Changes in the isotopic composition of lake water, seepage, groundwater, and inflowing or outflowing waters can help distinguish water sources and reveal changes in hydrological connectivity and mixing within the lake–dam system. When monitored through time, such signals may therefore provide evidence of hydrological reorganization—for example, the activation of new flow paths, increasing contributions from buried-ice melt or groundwater, or changes in water storage and exchange—that could accompany the development of unstable conditions. While at present there is no evidence for increasing frequency of GLOF after it peaked in the mid-20th century (Harrison et al., 2018; Shahgedanova et al., 2024), an emerging concern is associated with the outburst of ephemeral or non-stationary glacier lakes. This trend is evident, for example, in Central Asia where lakes can form over a single season and then outburst through subsurface drainage channels (Zaginaev et al., 2024).

3.2.3. Permafrost-related slope instability, landslides, debris flows

G Glacier thinning and retreat can locally reduce the support provided to adjacent valley walls, while atmospheric warming promotes permafrost degradation, ice loss within rock fractures, and reduced cohesion in frozen debris slopes. These processes can contribute to slope destabilisation and increase the availability of unconsolidated sediment potentially favouring rockfalls, rock avalanches, ice avalanches, debris flows, and rock-glacier dynamics. In the European Alps, several high-elevation rock and ice failures have been linked to warming permafrost and glacier retreat (Huggel et al., 2012; Fey et

al., 2025). In High Mountain Asia, debris flows remain primarily triggered by intense rainfall events; however, warming temperatures are contributing to an upward expansion of the debris-flow initiation zone through an increasing proportion of liquid precipitation at higher elevations and the degradation of formerly frozen slopes (Shahgedanova et al., 2024). Glacier retreat and permafrost thaw can further enhance hazard potential by exposing unstable valley walls, increasing sediment supply, and creating conditions in which mass movements may interact with glaciers, lakes, rivers, or downstream infrastructure (Zhang et al., 2024a). In the Andes, newly exposed slopes and moraine complexes are increasingly relevant for both local hazard management and long-term land use planning (Colavitto et al., 2024). Comparable processes are observed in Central Asia. In the northern Tien Shan (Kyrgyz Range, Kyrgyzstan), a high-altitude cryogenic landslide of about 0.9 million m³ occurred in June 2019 in the upper Kashka-Suu valley (Ala-Archa basin), initiating at 3,100–3,200 m within the permafrost zone and travelling about 950 m down-valley. Post-event surveys showed that roughly 85% of the displaced mass consisted of highly fractured, ice-bearing weathered bedrock, with frozen morainic debris (gravimetric ice content of 10–14%) and a 1–1.5 m layer of nearly pure buried ice exposed at the contact between the debris cover and the bedrock. Failure was preconditioned by deep permafrost thaw under a warming climate and by water impoundment along a fault-controlled bedrock step, which promoted progressive saturation of the fractured frozen rock mass and the overlying frozen debris (Erokhin and Zaginaev, 2019). This case illustrates how subsurface ground-ice degradation and structurally controlled subsurface water accumulation can precondition large slope failures in regions where such processes were previously not considered a significant hazard, and where surface indicators alone provided little forewarning. Increasingly, these effects are observed at higher elevations shifting zones of debris flow formation upwards (Shahgedanova et al., 2024).

3.3. A conceptual framework for cryosphere hazard assessment

3.2.1. Framework rationale

The proposed framework (Fig. 1) links five complementary dimensions: (i) potential hazard area (ii) baseline isotope and hydrochemical characterization; (iii) detection of internal hydrological reorganization, (iv) risk-informed decision logic that translates multi-signal evidence into priorities (v) development of policies.

3.2.2. Framework structure

Phase 1: System characterization - Understand the issue

The first phase aims to screen the relevant hazard types and characterize the physical and hydrological setting of the catchment. This includes documenting glacier geometry, slope steepness, the presence of glacial lakes and their characteristics, proximity to river channels, buried ice, permafrost, subsurface outlets, springs, and downstream exposure. These measurements could be performed by Unmanned

Aerial Vehicle (UAV) surveys, repeat satellite imagery, glacier geometry mapping, geophysical investigations such as GPR or ERT to identify buried ice and subsurface structures, and ground-temperature logging in permafrost terrain. The expected outcome is a hazard inventory and an initial conceptual hydrological model of the catchment, identifying the main water sources, flow pathways, storage zones, and potential instability features.

Phase 2: Seasonal baseline - Knowing about the past and present

The second phase aims to define the normal isotopic and hydrochemical routing regime across seasons. Seasonal sampling campaigns or after a specific event should be carried out. The recommended parameters include $\delta^{18}O$, $\delta^{2}H$, ^{222}Rn, annual ^{3}H, electrical conductivity (EC), water temperature, pH, major ions, and discharge.

Seasonal sampling campaigns should capture all relevant endmembers, including but not limited to precipitation, snow, glacier ice, firn, supraglacial and proglacial meltwater, groundwater, and streamflow. Complementary monitoring should include air temperature, precipitation, snow-cover dynamics, continuous discharge, lake level, suspended sediment, and ground temperature in permafrost terrain. These observations should establish the isotopic and hydrochemical signatures of the principal endmembers, thereby characterizing the range of natural seasonal hydrological variability against which future changes or potentially hazardous conditions can be assessed.

Phase 3: Detecting Changes

The third phase focuses on identifying deviations from the established baseline that may indicate internal hydrological change. Targeted high-frequency sampling should be implemented at key monitoring points, such as springs, lake outlets, seepage zones, dam discharge points, and proglacial outlets, during periods when destabilizing processes are most likely to occur. Such periods may include high-elevation heatwaves exceeding predefined temperature thresholds, prolonged or intense rainfall events, rapid snowmelt episodes, or other hydrometeorological conditions. By linking intensive monitoring to specific trigger conditions, sampling efforts can capture relevant hydrological responses while remaining operationally feasible and cost-effective. Warning triggers may include shifts in $\delta^{18}O$ and $\delta^{2}H$ away from baseline values. These isotopes and hydrochemical observations should be interpreted together with slope deformation monitoring, continuous discharge records, lake-level measurements, EC and temperature loggers, repeat UAV or satellite imagery, and, where possible, repeat geophysical surveys. The expected outcome is the recognition that the glacier, lake, permafrost slope, or catchment has shifted into a different hydrological state. This does not necessarily predict the exact timing of a hazardous event, but it provides evidence that the system has reorganized internally and may be more sensitive to external triggers such as intense rainfall, rapid snowmelt, heatwaves, or seismic disturbance.

Phase 4: Decision support and warning logic

The fourth phase translates multi-signal evidence into practical decision-support categories. Isotopic and hydrochemical observations are interpreted together with hydrometeorological, geomorphological, geophysical, and remote-sensing information to distinguish between normal seasonal variability and potentially hazardous system change. This phase does not aim to predict the exact timing of a hazard event. Rather, it supports state-based warning by identifying when a cryosphere-impacted system has shifted from a stable hydrological configuration toward a reorganized and potentially more sensitive condition. In this logic, isotope hydrology contributes to early-warning systems by detecting subsurface changes in water sources, flow pathways, storage, and connectivity that may not be visible from surface observations alone.

Phase 5: Strengthening resilience of cryosphere-impacted systems

The fifth phase focuses on translating scientific interpretation into actionable resilience measures for managers, practitioners, and policy developers. This phase ensures that isotope hydrology is not used only as a diagnostic tool, but also as part of a broader framework for risk reduction, adaptive management, and long-term resilience in glacier-fed and high-mountain catchments.

3.3. Isotopes for cryosphere-related hazard assessment

3.3.1. Hazard-specific isotope interpretation matrix

Isotope hydrology provides tools to investigate water storage, flow paths, and drainage processes that may influence the stability of glacierized and permafrost-affected mountain systems. Changes in subglacial and englacial drainage networks can alter basal water pressures, cavity development, and the accumulation and release of stored meltwater, potentially contributing to glacier instabilities, surface subsidence, leakage through moraine dams, or changes in the drainage of ice-dammed and moraine-dammed lakes (Kies et al., 2011; Yde et al., 2016). Stable water isotopes (δ^2H and $\delta^{18}O$), combined with EC and other hydrochemical tracers, can distinguish contributions from snowmelt, glacier melt, rainfall, groundwater, and subglacial drainage, allowing changes in runoff generation and water routing to be detected (Boral et al., 2019; Kumar et al., 2024). For hazard assessment, these tracers are particularly valuable for identifying increasing meltwater contributions during extreme melt periods, detecting the development of new drainage pathways, and recognizing leakage through moraine complexes or beneath glacier margins. In proglacial lakes, δ^2H-$\delta^{18}O$ relationships can be used to distinguish evaporative enrichment from direct meltwater inputs, while isotopic anomalies in lake outlets, springs, or downstream streams may indicate seepage through moraine dams, subsurface drainage routes, or changes in lake water balance (Dabrowski et al., 2020). Radon-222 and other natural radionuclides provide complementary information by identifying water that has interacted with sediments or bedrock, thereby helping to detect groundwater inflow, seepage pathways through moraine dams, or enhanced subsurface drainage beneath glaciers (Bhatia et al., 2011; Kies et al., 2011). In terrain affected by permafrost degradation, isotope and hydrochemical measurements can help distinguish water derived from seasonal snowmelt, rainfall, groundwater, thawing ground ice, or rock-glacier discharge (Bearzot et al., 2023; Skierzskan et al., 2023). Similarly, in moraine complexes, radon and uranium-series tracers can

provide evidence of groundwater inflow, internal seepage pathways, or prolonged water-rock interaction associated with dam instability (Lu et al., 2022; Skierzskan et al., 2024; Zhang et al., 2025). Together, these approaches reveal hydrological processes that are not directly observable from surface inspections. Their primary value for glacier-related hazard assessment lies in establishing a baseline hydrological architecture of glacierized catchments and potentially hazardous lakes, including the typical isotopic and hydrochemical signatures of precipitation, snowmelt, glacier melt, lake water, groundwater, and subsurface drainage pathways. Deviations from these baseline conditions may indicate evolving hydrological changes relevant to lake stability, glacier dynamics, permafrost degradation, or the potential development of hazardous conditions.

Table 1 translates these tracer applications into a hazard-specific interpretation matrix. It links each glacier-related or permafrost-related hazard system to the isotope tracers most relevant for detecting subsurface hydrological processes, the monitoring targets where these signals are expected to appear, and the possible interpretation of deviations from baseline conditions. The signals identified in the matrix should be evaluated together with complementary evidence, including discharge, lake level, EC, temperature, suspended sediment, slope deformation, geophysical surveys, remote-sensing observations, and geomorphic field indicators. In this sense, Table 1 **provides** a conceptual link between tracer-based process understanding and broader hazard assessment, while emphasizing the need for independent complementary observations. **Table S2** summarizes the proposed multi-parameter monitoring framework, highlighting how isotope tracers can be integrated with hydrological, geophysical, and remote sensing observations to identify subsurface hydrological changes, detect potential precursors of cryosphere-related hazards, and support the development and evaluation of early warning systems.

Table 1
Isotopic Tracers for Detecting Hydrological Reorganization in Gacier-Related Systems (hazard-specific interpretation matrix)

Hazard Type	Isotope	Specific Application	Monitoring Targets	Interpretation
Glacier Surge	$\delta^{18}O$ $\delta^{2}H$	Track changes in meltwater origin and drainage-system organization during pre-surge, active surge, and post-surge conditions	Proglacial streams, subglacial outlet	Shift in endmember proportions indicating drainage reorganization from distributed to channelized system (Bhatia et al., 2011; Yde et al., 2026)
	^{222}Rn	Indicate evolving subglacial or distributed drainage and increased water–rock interaction	Proglacial discharge, lateral seepage	Rising ^{222}Rn suggests shift toward distributed subglacial drainage with longer rock contact times (Linoff et al., 2017
Glacier Collapse	$\delta^{18}O$ $\delta^{2}H$	Characterize whether new outflows, springs, or runoff pulses derive from shallow melt, deeper glacier drainage.	New springs, runoff pulses, lateral seepage near unstable sectors	Appearance of deep-glacier or buried-ice isotopic signature in previously shallow-melt-dominated outflows (Wanner et al., 2023)
	^{222}Rn	Detect opening of new subglacial or englacial pathways; identify deeper distributed drainage activation	Seepage zones, new springs near glacier margins, proglacial discharge	^{222}Rnenrichment signals newly opened subglacial/englacial connections with enhanced rock interaction (Kies et al., 2011)
Ice Avalanche	$\delta^{18}O$ $\delta^{2}H$	Distinguish glacier-ice melt, snowmelt, rainfall and potentially different ice/water reservoirs	Runoff pulses, lateral seepage near unstable sectors	Increasing contribution of glacier melt or rapid shifts in water sources; filling/drainage of englacial water storage (Roy et al., 2024)
	^{222}Rn	Trace water that has interacted with the glacier bed, sediments or distributed subglacial drainage		Increased contribution of stored/subglacial water and changes in basal drainage connectivity

Hazard Type	Isotope	Specific Application	Monitoring Targets	Interpretation
Permafrost landslide	$\delta^{18}O$ $\delta^{2}H$	Distinguish active-layer meltwater, permafrost-origin water (relict/ground ice melt), shallow groundwater, and precipitation at seepage zones and springs on unstable slopes	Springs and seepage on landslide body, head scarp drainage, toe seepage, reference springs outside the failure zone	Isotopically depleted permafrost-ice signature in slope drainage indicates thawing of previously frozen ground; shift from baseline suggests increasing pore-water pressure and reduced slope stability
	^{222}Rn	Detect activation of deeper subsurface flow paths through thawing permafrost; distinguish shallow active-layer flow from deeper ground-ice melt with prolonged water–rock interaction	Seepage zones on slide surface, springs at landslide margins, groundwater wells in permafrost terrain	^{222}Rn enrichment at previously low-^{222}Rn seepage points signal newly opened deeper flow paths through degrading permafrost; sustained elevation indicates progressive thaw and potential for accelerated slope movement (Kipp et al., 2025)
GLOF	$\delta^{18}O$ $\delta^{2}H$	Vertical lake profiles to characterize inflow sources: snowmelt, glacier ice. Track changes in source contributions over time.	Lake water column (vertical profiles), lake outlet, dam seepage, inflow streams	Increasing buried-ice signature in lake or dam discharge warns of enhanced dam ice melt and higher breach/outburst risk (MacDonald., 2015)
	^{222}Rn	Detect increased melting of ice within lake dams; characterize subsurface flow through dam body	Dam discharge, seepage zones at dam toe, lake vertical profiles	Rising ^{222}Rnin dam discharge signals increasing contribution from melting ice within the dam, indicating growing instability (Luo et al., 2018)
	^{3}H	Age-date lake water and dam seepage to assess water source and residence time; distinguish recently recharged water from older stored components	Lake water, dam seepage, downstream springs	Shifts in ^{3}H indicate changing balance between recent precipitation input and older stored water or ice melt
	^{87}Sr ^{86}Sr	Fingerprint lithological sources of water entering the lake; discriminate between inflows draining different	Lake inflows, dam seepage, lake vertical profiles, reference samples from	Change in Sr ratio at dam seepage or lake outlet toward moraine/dam lithology signature indicates enhanced water–dam interaction and internal erosion; divergence from baseline warns of new

Hazard Type	Isotope	Specific Application	Monitoring Targets	Interpretation
		bedrock units, moraine material, and buried ice zones within the dam	distinct geological units	piping pathways through the dam; trace dissolution-precipitation processes in thawing permafrost (Monhonval et al., 2023).

3.3.2. Strategy for hydrochemical and isotope sampling design for system characterization, establishment of the baseline and detection of precursor of potential hazards

Figure 2 presents the first three phases of the proposed cryosphere-related hazard assessment framework, illustrating how isotope hydrology can be integrated with complementary hydrological, geophysical, meteorological and remote-sensing observations to progressively evaluate risk. These phases are intended to establish the reference conditions before an operational warning threshold can be defined. Figure 2 is intended as a flexible guide rather than a fixed sampling protocol, because the monitoring design must be adapted to the relevant hazard type, catchment accessibility, and available infrastructure.

An ideal case of an early-warning framework is presented in Fig. 3, showing how isotope and hydrochemical monitoring could help identify progressive hydrological reorganization before a potentially hazardous event. Four indicators—$\delta^{18}O$, ^{222}Rn, ^{3}H, and EC—are evaluated relative to their expected seasonal baseline, represented by the grey time series. The data used to build the ideal case is available in the **supplementary excel file S3**. During the seasonal baseline phase (blue), all parameters remain within their normal range and display only expected seasonal variability, allowing the normal hydrochemical and isotopic behaviour of the system to be established. In the precursor-detection phase (yellow), one or several parameters begin to deviate from this baseline. A shift in $\delta^{18}O$ may indicate the increasing contribution of a water source with a different isotopic signature, while enrichment in ^{222}Rn can indicate enhanced groundwater contribution or the activation of previously disconnected subsurface flow pathways. A progressive change in ^{3}H may reflect a modification in the relative contribution of younger or older water components, and an increase in EC can indicate the mobilisation of more mineralized water or the development of a new water–rock interaction pathway. During the escalation and impact phase (red), deviations become larger, persistent, and occur simultaneously across several independent tracers. The concurrence of a pronounced $\delta^{18}O$ shift, sustained ^{222}Rn enrichment, changing ^{3}H concentrations, and increasing EC could provide evidence of a substantial reorganization of the hydrological system than any individual parameter alone. This transition from isolated anomalies to coherent multi-parameter change forms the basis for moving from normal conditions to a deviation-detected state and ultimately to a potential critical/high-risk status.

4. Open Challenges

The proposed isotope-enabled monitoring framework integrates complementary dimensions of glacier-related hazard assessment, as demonstrated and discussed in this study. Given the complexity of glacier–hydrological systems and the multiple processes contributing to observed signals, several sources of uncertainty should be considered when applying and interpreting the proposed framework. First, isotope and hydrochemical signals are not unique indicators of specific hazard processes. Similar $\delta^{18}O$, $\delta^{2}H$, EC, or major-ion signatures may result from different combinations of snowmelt, glacier melt, groundwater, lake water, and buried-ice melt, particularly where endmember compositions overlap or vary seasonally. Interpretation therefore requires a robust baseline characterization and repeated sampling across hydrological conditions.

Second, short-lived tracers such as ^{222}Rn are sensitive to sampling protocol, degassing, temperature, turbulence, and the geometry of the flow path. Elevated ^{222}Rn may indicate groundwater inflow or longer water–rock contact, but it does not uniquely identify a specific subsurface pathway without supporting evidence from discharge, EC, temperature, geophysics, geomorphic mapping, or seepage observations. Similarly, tritium interpretation depends on analytical uncertainty, regional input functions, mixing, and the distinction between recent recharge and older stored water.

Third, isotope hydrology cannot predict the exact timing of glacial lake outburst floods, glacier collapse, landslides, or debris flows. Its role is diagnostic rather than deterministic. The framework should therefore be applied as part of a multi-signal assessment that integrates isotope and hydrochemical data with remote sensing, hydrometeorology, geotechnical observations, deformation monitoring, lake-level records, sediment data, and local field knowledge. Future work should test the framework in contrasting mountain settings and define which tracer combinations are most informative for specific hazard types.

5. Conclusion

This paper synthesizes evidence showing that isotope and hydrochemical observations can provide complementary information on hydrological reorganization associated with glacier-related hazards including the changes that may remain hidden from surface-based observations. Based on this synthesis, we propose an isotope-enabled framework that positions isotope and hydrochemical tracers as a diagnostic layer for identifying changes in water sources, groundwater connectivity, subsurface flow pathways, storage components, and residence times. The proposed framework does not provide a stand-alone method for predicting the timing of glacial lake outburst floods, glacier collapse, slope failures, or debris flows. Rather, it supports state-based interpretation when tracer anomalies are evaluated together with hydrometeorological triggers, geomorphic instability, geophysical evidence, remote-sensing observations, and field-based indicators. This article further highlights an urgent need to integrate isotope hydrology more systematically into existing glacier and mountain-hazard monitoring strategies. Such integration can help bridge the gap between surface expressions of instability and the underlying hydrological processes that control or accompany hazard development, providing an additional line of evidence for detecting evolving system states. Future focus should test the framework

in contrasting mountain settings, including moraine-dammed lakes, debris-covered glacier systems, permafrost-affected slopes, and glacier-fed basins exposed to cascading hazards.

Declarations

Data availability

All data generated or analyzed during this study are included in this published article and its supplementary information files.

Statements & Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Melanie Vital, Hatice Turk and Yuliya Vystavna. The first draft of the manuscript was written by Melanie Vital, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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