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Open Access Earth System Science Data Discussions

Large-scale isotopic fingerprinting of cryosphere and hydrological components in glacierized catchments

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Abstract. Stable water isotopes (SWI; $\delta^{18}O$ and $\delta^{2}H$) are widely used tracers for identifying water sources and reconstructing hydroclimatic processes in glacierized catchments. However, globally harmonized isotope datasets that integrate multiple cryosphere and hydrological endmembers remain limited. Here we present a global georeferenced database of stable water isotope measurements compiled across glacierized catchments worldwide. The dataset contains 12,348 individual $\delta^{18}O$ and $\delta^{2}H$ measurements collected from 63 publications, covering 19 countries across six continents. The temporal coverage of the isotope measurements spans from 1978 to2023, based on data compiled from publications starting in 1981. The database integrates isotope measurements from precipitation, snowpack and snowmelt, glacier ice, firn, glacial and supraglacial meltwater, rock glaciers, ice-cored moraines, permafrost thaw waters, talus slopes, streams, lakes, and groundwater. Each record includes standardized metadata describing geographic location, elevation, sampling period, endmember classification, and analytical methods. Across the compiled dataset, $\delta^{18}O$ values range from approximately −31‰ to −0.36‰, while $\delta^{2}H$ values range from −247‰ to 0‰, reflecting strong variability in elevation, temperature, and moisture source conditions across glacierized environments. Cryosphere endmembers such as glacier ice and glacial meltwater typically exhibit depleted signatures ($\delta^{18}O \approx -14$‰; $\delta^{2}H \approx -100$‰) reflecting precipitation formed under colder climatic conditions and preserved within glacier storage, while groundwater and firn waters tend to show relatively enriched compositions due to mixing, recharge processes, and seasonal precipitation inputs. By harmonizing isotope observations across multiple cryosphere and hydrological components, this database provides a new global reference for identifying characteristic isotopic signatures of glacier-derived waters and their downstream mixing with other hydrological sources. The dataset supports comparative studies of glacier–hydrology interactions, endmember mixing analysis, and isotope-enabled hydrological modelling, contributing to improved understanding of water resources in glacier-fed catchments under changing climate conditions. The dataset is publicly available at https://doi.org/10.5281/zenodo.19062383 (Vital et al., 2026).

1. Introduction

Glaciers act as long-term freshwater reservoirs, help regulate seasonal river flows, and are sensitive indicators of climate change (Huss et al., 2018; Clason et al., 2023). In many mountai regions, glacier melt sustains river discharge during dry and warm periods, supports downstream ecosystems and provide water supplies to communities. Also, glaciers buffer hydrological

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extremes by moderating both low-flow conditions and peak runoff (Millet et al., 2012; Laurent et al., 2020; Slemmons et al., 2013; Viviroli et al., 2020).

Glacierized regions are unevenly distributed across the globe, with the largest glacierized areas found in high-latitude environments and major mountain belts (RGI 7.0 Consortium, 2023). The world's largest glacierized region outside the polar ice sheets is situated in High Mountain Asia, including the Himalaya, Karakoram, ad Hindu Kush which together store vast volumes of ice and sustain major river systems (Clason et al., 2023). Additional glacierized systems occur in Central Asia, Pamir, and Tien Shan, which are commonly treated as separate glacier regions due to their distinct tectonic setting and continental climate regime. Other major glacierized regions include the Arctic and sub-Arctic of North America (Alaska and the Canadian Arctic), the Andes of South America, the Patagonian Ice fields, the European Alps, the Southern Alps of New Zealand, and the high mountains of the Caucasus and the Altai and Sayan mountain systems (Li et al., 2023).

Although Antarctica and Greenland represent 40% of the global glacier ice volume (Li et al., 2023), their hydrological settings differ from mountain catchments. In mountain catchments, meltwater is typically routed through well-defined pathways, flowing over (supraglacial), through (englacial) and beneath (subglacial) glaciers and seasonal snowpacks into proglacial streams, and subsequently into river networks (Sharp and Tranter, 2017). Along this transit, a significant fraction of meltwater may also infiltrate into the shallow subsurface, where it can be temporarily stored in soils, talus slopes, moraines, or fractured bedrock, either in liquid or solid form, contributing to shallow groundwater and delayed baseflow (Glas et al., 2018; Gordon et al., 2015). In contrast, in polar environments, surface drainage networks are often sparse, discontinuous, absent or are draining directly towards the surrounding oceans, with restricted contribution to terrestrial hydrologic cycles (e.g., Perșoiu et al., 2023). For this reason, this study focuses on glacierized systems at the continental scale where glaciers interact directly with surface waters and groundwater.

Glaciers respond directly to variations in air temperature and precipitation through changes in accumulation and melt and their evolution reflects the integrated effects of climatic forcing over timescales ranging from seasons to decades (Thompson et al., 2003). In this context, stable water isotopes (SWI) are natural constitutes of the water molecule that can be used as tracers for reconstructing past and present hydroclimatic conditions (Yoshimura, 2015; Dee et al, 2023, Kim, 2025). Stable oxygen and hydrogen isotopes in the water molecule ($\delta^{18}O$ and $\delta^{2}H$) record information on moisture sources, elevation and temperature controls on glacier accumulation

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and ablation, and post-depositional modification of precipitation signals, all of which are essential for understanding the functioning of glacierized catchments. Moreover, SWI enable the quantitative separation of cryosphere and hydrological contributions to streamflow (Wanner et al., 2023; Dee et al., 2023; Müller et al., 2025; Evans, 2025). Consequently, integrating SWI analysis into studies of glacierized catchments can be used to assess how glacier-derived water resources are likely to evolve in response to ongoing climate change. This study presents the first global compilation of SWI data from diverse hydrological components that represent cryosphere in catchments, including the diversity of endmembers: precipitation, stream, lakes, groundwater, snowpack, snow melt, glacial meltwater, supraglacial meltwater, firn, glacier ice, ice-core moraines, rock glacier, permafrost thaw, and talus slopes. While $\delta^{18}O$ and $\delta^{2}H$ have been extensively determined in individual components of the hydrosphere (e.g. Penna et al., 2014, Chen et al., 2024), through global monitoring networks such as GNIP and GNIR (Craig, 1961; Rozanski et al., 1993; Vitvar et al., 2007, IAEA/WMO, 2025), and in regional studies (e.g.,Taylor et al., 2001; Vreča et al., 2006, Vodila et al., 2011; Rets et al., 2019; Zhe et al., 2022; Lin et al., 2024, Saidaliyeva et al., 2024; Chen et al., 2024a; Bai et al., 2025; Avesani et al., 2025; Nguyen et al., 2025; Li et al., 2025a, 2025b), a comprehensive, harmonized dataset integrating cryosphere, surface, and subsurface waters at the global scale has not previously been available.

The novelty of this work lies in its integration of multiple cryosphere and hydrological components into a single georeferenced database that covers the spatial distribution of the cryosphere in inhabited regions. This approach enables direct comparison of SWI signatures across endmembers, continents, and climate regimes, revealing fractionation patterns and regionally specific deviations driven by climate, elevation, and hydrological processes (Dansgaard, 1964; Rozanski et al., 1993; Bojar, 2021; IAEA, 2022, Zhe et al., 2022). The database (Vital et al., 2026) supports a wide range of applications, including: aid in selection of appropriate secondary standards to cover the anticipated range in isotope ratio when making measurements on samples from new field sites; isotope-based hydrograph separation and endmember mixing analysis (Christophersen & Hooper, 1992; Kendall & McDonnell, 1998; He, 2019; Arora, 2024; Dar, 2024; Muller, 2025); calibration and evaluation of isotope-enabled hydrological models in glacierized catchments (Ala-aho et al., 2017; Bowen et al., 2019; IAEA 2025), estimation of transit time (Staudinger et al., 2020) and the development of data-driven and artificial intelligence (AI) -based predictive models of water balance and cryosphere–hydrology interactions. Further, by using spatial distribution of SWI signatures in different endmembers in different climates as a proxy for

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climate variability, it allows for a better understanding of their dynamics in response to past processes and thus robust prediction for their future response to ongoing climatic changes (Vuille et al., 2020; Vystavna et al., 2021, 2024).

2. Data and Methods

2.1. Endmembers definitions

In hydrology and geochemistry, endmembers represent the pure or unmixed water sources that contribute to a mixture (Christophersen & Hooper 1992). Endmembers are idealized source of water at the boundaries of the mixing space. Table 1 provides a definition for each endmember used in this study, including precipitation, stream, lakes, groundwater, snowpack, snowpack melt, glacial meltwater, supraglacial meltwater, firn, glacier ice, ice-core moraines, rock glacier, permafrost thaw, and talus slopes.

Table 1. Definitions and key references for hydrological and cryosphere endmembers included in the isotope database in glacierized catchments.

Endmembers	Definition	References
Precipitation	Meteoric water, including liquid, solid and mixed precipitation, isotopic composition governed by temperature, humidity, and source, following the Global Meteoric Water Line (GMWL).	Craig, 1961; Dansgaard, 1964
Stream	Integrates contributions from precipitation, snow, glacier melt, and groundwater.	Kendall and Coplen, 2001
Lakes	Reservoir water under open-water evaporative conditions. Its isotopic composition commonly shows enrichment along an evaporation line controlled by humidity wind and temperature	Gibson et al., 2002; Horita et al., 2008
Groundwater	Subsurface water integrating multiple recharge events over time; well mixed, isotopic values are damped relative to precipitation, indicative of recharge conditions, pattern and timing.	Clark and Fritz, 1997; Jasechko, 2017
Snowpack	Seasonally accumulated snow stored on the ground prior to melting. Snowpack isotopic composition integrates mainly winter precipitation signals and may be modified by sublimation, wind redistribution, summer rain events and melt–refreeze cycles.	Clark and Fritz., 1997; Taylor et al., 2001

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Snowpack melt	Seasonal meltwater from snowpacks, often with lower $\delta^{18}O$ and $\delta^{2}H$ values compared to rainwater; key source of runoff in cold and mountain basins.	Taylor et al., 2001; Penna et al., 2014
Glacier meltwater	Meltwater derived from glacier ice; with lower $\delta^{18}O$ and $\delta^{2}H$ values compared to the stream water and precipitation due to sourcing from accumulation of cold-season precipitation and/or relict ice formed in past colder climates.	Jansson et al., 2003; Immerzeel et al., 2010
Supraglacial meltwater	Liquid water on the surface of a glacier, formed by the melting of snow and ice.	Müller et al., 2025
Glacier ice	Solid glacial mass formed from accumulated and compacted snow through firnification. Its meltwater represents a primary cryosphere endmember, typically depleted in heavy isotopes due to elevation effects, temperature-dependent fractionation, and Rayleigh distillation during snowfall.	Dansgaard, 1964
Firn	Partially compacted old snow, intermediate between snow and glacier ice in terms of density.	Ala-aho et al., 2017
Ice cored moraines	Morainic deposits that contain buried glacier ice beneath a cover of debris. Meltwater derived from ice-cored moraines typically reflects glacier ice isotopic signatures but may be altered by partial refreezing of meltwater within the moraine body.	Humlum, 2000
Rock glacier	Distinct bodies of a perennially frozen debris–ice mixture covered by a seasonally thawed debris layer.	Amschwand et al., 2025
Permafrost thaw	Water released during the thawing of previously frozen ground (permafrost), including ice-rich soil, ground ice, and buried glacier ice. Its isotopic composition reflects the original meteoric water preserved at the time of freezing, modified by freezing and thawing processes.	Woo, 2012
Talus slopes	Liquid water draining from coarse, steep debris accumulations at the base of cliffs or valley walls. Talus-slope waters often reflect rapid infiltration of snowmelt or precipitation with limited mixing, and in cold regions may include meltwater from interstitial ice or seasonal frozen ground.	Curry et al., 2023

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155 **2.2. Data collection and Data quality**

156 The database contains 12,348 individual entries describing the isotopic signatures of hydrological
157 endmembers obtained from 63 publications. The list of publications used to build this database is
158 available in Supplementary material (Table S1). The database only includes single data; averages
159 of isotopic values are not included in this study. It extends to all inhabited continents, with
160 coverage across 20 countries and multiple climatic regions. The temporal coverage extends from
161 1981 to most recent publications (up to 2025). Peer-reviewed publications were identified
162 through systematic searches in major scientific databases, primarily Web of Science and Scopus.
163 Keyword combinations included “stable water isotopes”, “glacier meltwater”, “snowmelt
164 isotopes”, “cryosphere hydrology”, “glacierized catchments”, “$\delta^{18}O$”, and “$\delta^{2}H$”. In addition to
165 published sources, the database also integrates non-published isotope datasets collected directly
166 by the authors of this study. Each record includes 44 fields grouped into four categories:
167 bibliographic metadata (data owner, publication year, citation, published status); geographical
168 metadata (continent, country, catchment, glacier name, basin, coordinates); sampling details
169 (sample type, number of samples, sampling period, elevation, remarks); and stable isotope data
170 ($\delta^{18}O$, $\delta^{2}H$, d-excess, method, error, uncertainty) and sources (references). Endmember labels
171 were standardized to a controlled vocabulary used in endmember mixing analysis (EMMA). The
172 data were reported in $\delta^{18}O$ and $\delta^{2}H$ relative to VSMOW/VSMOW2 with units in per mil (‰). The
173 deuterium-excess (d-excess) was reported or calculated as $\delta^{2}H - 8 \cdot \delta^{18}O$ (Dansgaard, 1964).
174 Reported measurement techniques include isotope ratio mass spectrometry (IRMS) and laser
175 spectroscopy (Cavity Ring-Down Spectroscopy – CRDS and Off-Axis Integrated Cavity Output
176 Spectroscopy – OA-ICOS). The analytical methods reported for $\delta^{18}O$ measurements include CRDS:
177 9,192; IRMS: 2,738; OA-ICOS: 418. The same distribution applies to $\delta^{2}H$ analyses. The mean
178 reported one-sigma analytical uncertainties are approximately 0.13‰ for $\delta^{18}O$ and 0.49‰ for
179 $\delta^{2}H$. Outliers were flagged rather than removed for $\delta^{18}O$ values outside [−40, +20] ‰, for $\delta^{2}H$
180 values outside [−320, +120] ‰. Values of deuterium excess outside the range [+0, +25] ‰ were
181 carefully flagged for further verification. While most precipitation globally exhibits d-excess values
182 close to +10 ‰, unusually high values may occur in cryosphere environments. Elevated d-excess
183 can result from kinetic fractionation processes associated with sublimation and vapor exchange
184 in snowpacks, glacier surfaces, and supraglacial environments, particularly under conditions of
185 low relative humidity and strong wind. Post-depositional modification of snow and ice may also

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alter the original isotopic signal. In addition, extremely high values may occasionally reflect analytical artefacts or transcription errors in the original sources. Flagging these records therefore allows potentially modified or uncertain measurements to be identified while retaining them in the dataset for transparency.

2.3. Data distribution

The isotope records are mostly clustered in Europe, particularly in the Alpine region (Fig. 1). Additional major clusters occur in Asia, particularly in China and the broader High-Mountain Asia domain, and in western North America, including Alaska, the Canadian Rockies, and mountainous regions of the United States. Smaller clusters are present in the Andes of South America and in selected sites in East Africa. Coverage in Oceania and other parts of Africa remains sparse. Overall, the database comprises 12,348 records distributed across 20 countries and six continents: Europe (5,899), Asia (3,132), North America (3,022), South America (249), Africa (32), and Oceania (12). The catchments included in this study are concentrated in mountain regions outside the major polar ice sheets: Asia, South America, and Europe together represent 75.0% of the study catchments (28.1%, 26.6%, and 20.3%, respectively), despite accounting for only ~33% of global glacier ice volume (Table 2). North America contributes 18.8% of the catchments, broadly consistent with its large global share of glacier area and volume.

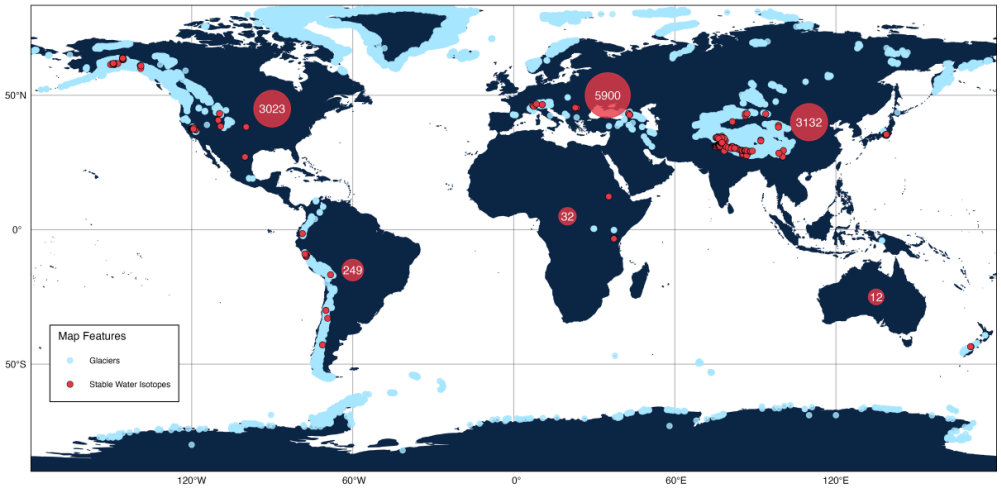

Figure 1. Global map showing the geographic distribution of glacierized continental catchments outside the major polar ice sheets included in the isotope endmember database. Red markers

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indicate individual study locations, while red circles represent regional clustering with the number of records compiled per region. This study focuses on glacierized systems at the continental scale where glaciers interact directly with surface waters and groundwater.

Table 2. Regional distribution of glacier area and ice volume derived from Li et al. (2023), compared with the number and proportion of glacierized catchments included in the isotope database. The table summarizes global glacier area (km² and %), global ice volume (km³ and %), and the representation of study catchments by region, highlighting the spatial coverage of isotopic observations relative to global cryosphere distribution.

Region	Global area (km²)	Global area (%)	Global ice volume (km³)	Global ice volume (%)	Number of catchments in this study (n)	catchments (%)
Africa	5	<0.1	0.2	<0.1	1	1.6
Asia	152915	21.7	25249	16.3	18	28.1
Europe	50060	7.1	11025	7.1	13	20.3
North America	247251	35.0	51593	33.2	12	18.8
South America	31760	4.5	6117	3.9	17	26.6
Oceania	1164	0.2	72	0.1	3	4.7

3. Uncertainty, challenges and limitations in the construction of isotope datasets

Uncertainty is an inherent component of any large-scale environmental dataset, particularly when it integrates measurements originating from multiple studies, laboratories, and sampling contexts. In the present compilation of stable water isotope records from glacierized catchments, uncertainty arises from several sources, including analytical precision of isotope measurements, natural environmental variability, heterogeneity in sampling strategies, and limitations associated with the integration and harmonization of datasets from diverse publications. Rather than representing a single numerical value, uncertainty in this database should be understood as the combined effect of these factors, which influence the interpretation and comparability of isotope data across spatial and temporal scales.

3.1. Uncertainty related to analytical precision

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A first level of uncertainty relates to analytical precision in the measurement of stable water isotopes (δ^2H and $\delta^{18}O$). Most measurements included in this dataset were originally generated using isotope ratio mass spectrometry (IRMS) or cavity ring-down spectroscopy (CRDS), both widely used techniques in isotope hydrology. Under standard laboratory conditions, these analytical systems typically achieve precisions on the order of ±0.1‰ for $\delta^{18}O$ and ±0.5–1.0‰ for δ^2H. Calibration procedures generally rely on internationally recognized reference materials, including Vienna Standard Mean Ocean Water (VSMOW2), Standard Light Antarctic Precipitation (SLAP2), ensuring comparability between laboratories operating within the international isotope measurement framework. However, the dataset compiles results produced over several decades and across many analytical facilities, meaning that reported precision may vary slightly depending on instrument configuration, laboratory calibration procedures, and the analytical protocols applied at the time of measurement. Where available, information on analytical precision reported in the original publications was retained in the metadata, although such information was not consistently provided across all studies. Elevated d-excess allows to flag uncertainty in analytical precision, analytical artefacts, or transcription errors in the original sources.

3.2. Uncertainty related to environmental variability

Beyond laboratory precision, a significant component of uncertainty arises from environmental variability and hydrological processes that influence isotope compositions in glacierized catchments. Stable isotope signatures of water reflect integrated atmospheric and hydrological processes including condensation history, temperature conditions during precipitation formation, evaporation, sublimation, and mixing of different water sources. In glacierized environments, additional processes such as snow metamorphism, meltwater refreezing, supraglacial evaporation, and subglacial water storage can further modify isotope signatures. As a result, differences observed between samples are not necessarily indicative of analytical error but rather represent natural variability within the hydrological system. For instance, precipitation samples may represent individual storm events, daily collections, or monthly composite samples depending on the monitoring network. Similarly, glacier meltwater samples may represent instantaneous stream samples, integrated catchment discharge, or localized supraglacial melt. These differences introduce variability in isotope values that reflects real hydrological heterogeneity rather than measurement uncertainty alone.

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3.3. Variability related to temporal sampling

Temporal sampling differences also contribute to variability within the dataset. Some records represent long-term monitoring programs spanning multiple years, while others correspond to short field campaigns or isolated sampling events. Seasonal processes are particularly important in glacierized basins, where isotope compositions can vary substantially between winter snow accumulation, spring snowmelt, and late-summer glacier melt contributions. Consequently, comparisons among studies should consider the temporal context of sampling, as differences in seasonality can influence the isotopic composition of measured water bodies. The database attempts to preserve this information through metadata fields describing sampling date, sampling context, and environmental conditions whenever such information was available in the source publications.

3.4. Variability related to spatial heterogeneity

Spatial heterogeneity represents another source of uncertainty in the interpretation of isotope patterns. Glacierized catchments often exhibit strong elevation gradients, complex topography, and localized microclimatic conditions that influence precipitation isotope composition and meltwater generation. Isotopic lapse rates associated with altitude can lead to systematic depletion of heavy isotopes at higher elevations, while local factors such as wind redistribution of snow, sublimation, and differential melting may introduce additional variability. Because many compiled studies sampled different parts of a catchment system—such as glacier surfaces, proglacial streams, downstream rivers, or nearby groundwater systems—observed isotope differences may reflect spatial sampling differences rather than inconsistencies in analytical results. Another limitation relates to potential biases in the spatial distribution of available data. Stable isotope measurements in glacierized environments are unevenly distributed geographically, reflecting differences in research infrastructure, accessibility of field sites, and historical research priorities. Well-studied regions such as the European Alps, North American mountain ranges, and parts of Asia tend to have higher densities of isotope measurements compared to remote or logistically challenging glacier regions. As a result, the dataset may not fully capture the global diversity of isotope signatures across all glacierized basins. Users performing global-scale analyses should therefore consider potential regional sampling biases when interpreting spatial patterns or deriving global relationships. For this reason, the geographic coordinates and elevation of sampling locations were retained as core metadata fields to enable

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spatially explicit analyses and allow users to evaluate potential altitude or catchment-scale effects.

3.5. Variability related to metadata

The integration of heterogeneous datasets into a unified database also introduces uncertainty related to data harmonization. Source publications vary in how isotope values are reported, including differences in units, reference scales, coordinate systems, and terminology used to describe sample types. Data were reported to VSMOW-SLAP, 2 point normalization (‰). Records lacking essential contextual information such as geographic location, sample type, or isotope units, were excluded or flagged during quality control procedures. Nevertheless, some degree of uncertainty remains inherent when combining datasets generated under different scientific objectives and reporting frameworks. Metadata completeness represents an additional limitation of the dataset. While the database includes a standardized set of metadata fields describing geographic, environmental, and analytical attributes of each sample, not all publications reported the full set of information. For example, analytical uncertainty values, sampling depth, or detailed descriptions of sampling context were sometimes absent from the original sources. In such cases, the dataset preserves the available information without attempting to infer missing parameters. This approach prioritizes transparency and avoids introducing assumptions that could bias subsequent analyses. However, users should be aware that incomplete metadata may limit certain types of quantitative assessments, particularly those requiring precise information on sampling conditions or laboratory analytical performance. Despite these limitations, the compilation provides several mechanisms that allow users to evaluate and propagate uncertainty in downstream analyses. The standardized classification of endmember types (e.g., precipitation, snowpack, glacier ice, meltwater, groundwater) enables statistical comparison of isotope distributions within and between hydrological components. Measures such as variance, interquartile range, and confidence intervals can be used to quantify the dispersion of isotope values within each category, providing insight into both environmental variability and potential analytical uncertainty. Similarly, regression analyses used to derive global or regional isotope relationships can incorporate statistical measures of uncertainty such as confidence intervals.

In summary, uncertainty in this dataset should be interpreted as the combined outcome of analytical precision, environmental variability, methodological differences among studies, and limitations associated with data integration and metadata completeness. The database addresses

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these challenges through transparent documentation, metadata standardization, and quality-control procedures designed to maximize comparability among records while preserving the contextual information necessary for scientific interpretation. Users are encouraged to consider these sources of uncertainty when applying the dataset to hydrological analyses, isotope-based mixing models, or regional comparisons of water isotope signatures in glacierized catchments.

4. Results and discussions

4.1. Distribution of cryosphere and hydrological endmembers

Data were plotted using a Dual-isotope diagram (δ^2H vs. $\delta^{18}O$, ‰ VSMOW) showing the distribution of cryosphere and hydrological endmembers compiled from glacierized catchments (Figure 2). Most observations cluster along the GMWL (GMWL: $\delta^2H = 8 \cdot \delta^{18}O + 10$; Craig, 1961), the isotope signatures therefore largely preserve the original meteoric signal. The possible dominant influence of high-altitude and cold climate in glacierized catchments can result in minimal kinetic fractionation and endmembers isotopic compositions that remain close to the GMWL (Gibson et al., 2002). All waters display negative δ^2H values relative to VSMOW and VSMOW2, reflecting precipitation formed under progressive rainout during atmospheric transport and inherited by glacier, firn, meltwater, groundwater, and lake components with limited post-depositional fractionation and preservation of the original climatic signal (Olliver et al., 2025). The general regression line shows a slope close to that of the global meteoric water (8.23), indicating isotope fractionation dominated by equilibrium condensation rather than evaporation. The relatively high intercepts (≈15‰) correspond to elevated d-excess values and reflect evaporation under non-equilibrium conditions at the moisture source (e.g., in atmospheres with low relative humidity, Pfahl and Sodemann, 2014). Precipitation in cold and high-latitude regions often originates from cold oceans, sea-ice margins, or continental surfaces where the air is dry. These characteristics are commonly associated with cold-season precipitation and long-range atmospheric transport, and they are preserved in snow, ice, meltwater, and downstream waters due to minimal post-precipitation evaporation (Merlivat and Jouzel, 1979). Liquid waters derived from cryosphere environments (ice-cored moraine, talus slopes, supraglacial meltwater, rock glacier outflow, and permafrost thaw) also plot close to the GMWL. Stream and lake waters show comparable patterns, overlapping with precipitation, snowpack, and glacial meltwater. This implies that precipitation, snowmelt, and glacial melt entering the system at different times are mixed and averaged through storage and transport processes. As a result, short-term or seasonal

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isotopic variability is not observed. For the lake endmember, this behaviour particularly contrasts with observations from arid and semi-arid regions, where lakes often show pronounced enrichment in heavier isotopes and deviation from the meteoric water line due to high evaporation, long residence times, and warm climatic conditions and therefore plot along the Global Evaporation Line for Lakes, GEL: $\delta^2H = 5.5 \cdot \delta^{18}O - 3$ (e.g., Vystavna et al., 2021).

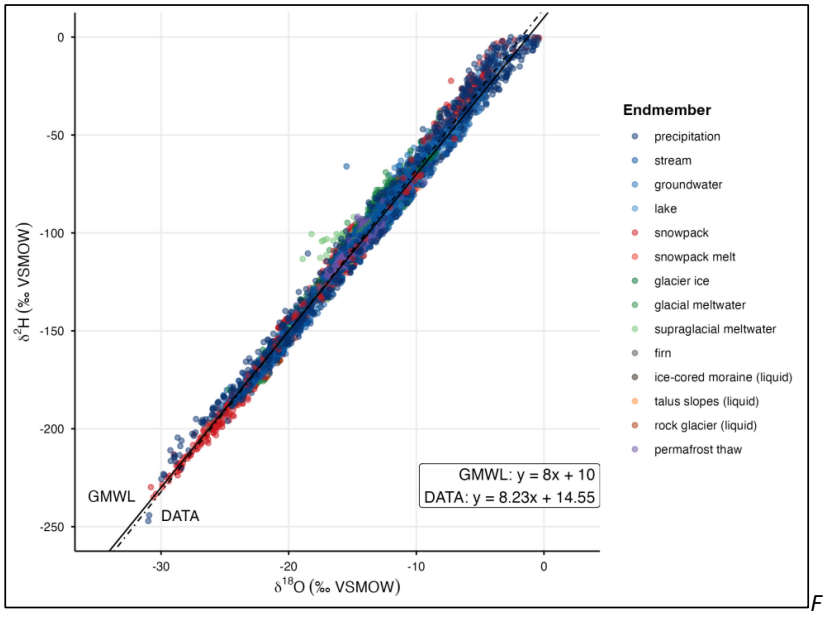

Figure 2. Dual-isotope diagram (δ^2H vs. $\delta^{18}O$, ‰ VSMOW) showing the distribution of cryosphere and hydrological endmembers compiled from glacierized catchments worldwide. Coloured symbols represent different water types, including precipitation, stream, lakes, groundwater, snowpack, snowpack melt, glacial meltwater, supraglacial meltwater, firn, glacier ice, ice-core moraines, rock glacier, permafrost thaw, and talus slopes. The Global Meteoric Water Line (GMWL: $\delta^2H = 8 \cdot \delta^{18}O + 10$) is shown for reference.

4.2. Global variations of stable water isotopes values in hydrological and cryosphere endmembers

The boxplots in Figure 3 summarize $\delta^{18}O$ (‰ VSMOW and VSMOW2) across the compiled global dataset, grouped by hydrological endmember types. Ice-cored moraines, lake, talus-slopes, snowpack and supraglacial meltwater, exhibit the most ^{18}O-depleted isotopic signatures,

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generally, between −25 and −10‰. These values are consistent with derivation from long-term snow and ice accumulation formed under cold conditions and limited post-depositional modification (Taylor et al., 2001; Penna et al., 2014) during repeated melt and freeze cycles. Unlike lowland (Aichner et al., 2022) or arid settings, the lakes in this dataset do not show strong isotopic enrichment. Their median value of $\delta^{18}O$ of approximately −17 ‰ overlap with those of other cold-region surface waters. This pattern is consistent with the dominance of high-altitude, cold environments, where ice-free periods are short and evaporation is limited (Gat, 1996; Gibson & Edwards, 2002). Isotopic signatures of surface water endmembers, lakes and streams, are consistent with the values in the region established by Li et al. (2025b). Glacier ice, rock glacier, permafrost thaw, stream and glacial meltwater exhibit slightly less ^{18}O-depleted isotopic signatures (approximately −15‰). Snowpack and glacial meltwater display a broad variability possibly due to the diversity of sampling methods and melting approach before analysis that are not standardized yet. Sampling cryosphere endmembers is still a challenge. Also, seasonal snow reflects the precipitation variability. Seasonal fractionation during snowfall, redistribution within the snowpack, and progressive enrichment in heavy isotopes during melt and refreezing cycles (Dansgaard, 1964; Jouzel and Souchez, 1982; Taylor et al., 2001) can also explain the high variability in snowpacks. This comparison may benefit from clearer spatial and temporal constraints (e.g., elevation, season). for instance, in monsoon-dominated regions such as Yulong Snow Mountain, Lijiang, snowpack meltwater has been observed to be isotopically heavier than rainwater (Pu et al., 2020; Shi et al., 2020). Precipitation exhibits the widest spread of $\delta^{18}O$ values, extending from −30 to 0‰, capturing the combined effects of latitude, elevation, temperature, and moisture source variability.

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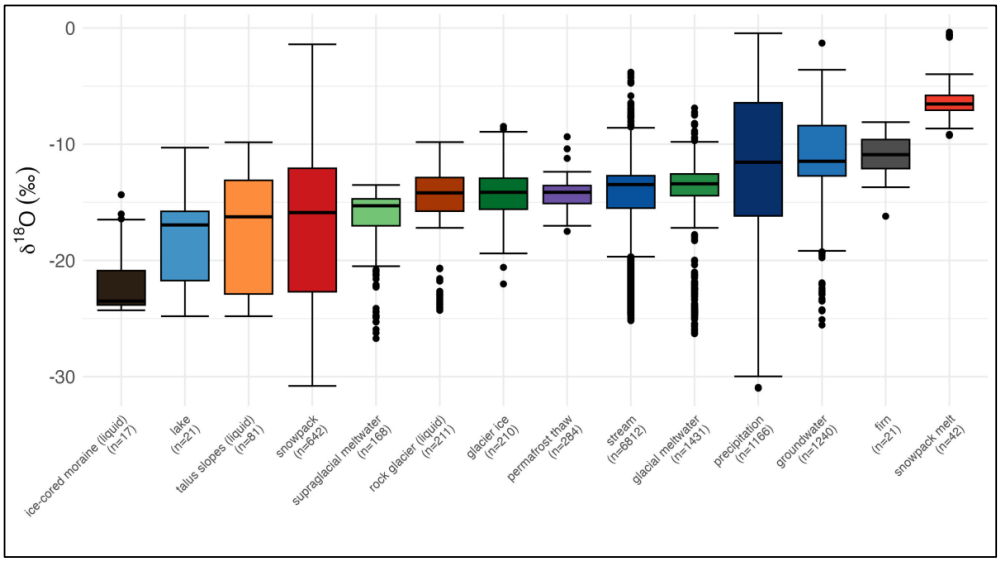

Figure 3. Boxplots showing the distribution of $\delta^{18}O$ (‰) values across cryosphere and hydrological endmembers in glacierized catchments. Each box represents the median, interquartile range, and variability of isotopic composition for a given water type, with whiskers indicating data spread and points representing outliers. Sample sizes (n) are indicated for each category along the x-axis. The figure illustrates systematic isotopic differences among solid cryosphere components (firn, snowpack, glacier ice), liquid meltwater sources, groundwater, and precipitation, highlighting enrichment trends associated with melt processes, evaporation, and hydrological mixing.

4.3. Continental variations of stable water isotopes values in hydrological and cryosphere endmembers

The boxplots in Figure 4 illustrate continental-scale variations in $\delta^{18}O$ for selected hydrological endmembers across Africa, Asia, Europe, North America, and South America. To represent major climatic and hydrological contrasts across North America, the boxplots were separated at 60° latitude, which marks the transition between sub-Arctic/Arctic and temperate–alpine environments. Regions north of 60°, including Alaska, Yukon, and the Canadian Arctic Archipelago, are characterized by persistently cold conditions, widespread permafrost, and precipitation dominated by cold-season snowfall formed under low temperatures and long atmospheric transport pathways (Pfahl & Sodemann, 2014; Terzer-Wassmuth et al., 2021; Chen et al., 2020).

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These conditions lead to strong isotopic fractionation and very low $\delta^{18}O$ and $\delta^{2}H$ values, with d-excess primarily reflecting moisture-source characteristics (Dansgaard, 1964). In contrast, regions south of 60° are dominated by temperate and alpine climates with longer melt seasons, more diverse precipitation regimes, and a stronger influence of local moisture recycling and secondary evaporation.

These climatic differences are directly reflected in the isotopic composition of hydrological endmembers. North of 60°, glacier ice, meltwater, snowpack, groundwater, and streams exhibit very low $\delta^{18}O$ values, with median values frequently below −20‰, indicative of cold continental and high-latitude environments. Stream waters reflect mixing between cryosphere and meteoric sources, resulting in intermediate values that nonetheless indicate a dominant contribution from glacier and snowmelt. South of 60°, all endmembers shift towards less negative isotope values. Although glacier ice and meltwater remain relatively ^{18}O-depleted, precipitation and groundwater are more ^{18}O-enriched (typically around −15 to −10‰), consistent with milder conditions and greater influence of lower-latitude moisture sources, while streams display a broad range of values reflecting variable source mixing (Zang et al., 2024). Overall, North America exhibits the widest range of isotope values among the continents considered in this study, reflecting strong latitudinal and elevational gradients combined with contrasting precipitation regimes and complex hydrological mixing processes (Dansgaard, 1964; Bowen and Revenaugh, 2003). Similar numbers of isotope measurements are available for both North America and Asia, and more for Europe, suggesting the greater variability observed in North America is real rather than a sample size artefact.

South America exhibits marked isotopic gradients influenced by the Andean uplift and the contribution of moisture sources from the Amazon and the Pacific. In high mountain areas, such as Nevado Huascarán (Cordillera Blanca, Peru), glacial meltwater shows depleted $\delta^{18}O$ values (typically between -18 and -14‰), resulting from orographic uplift and the progressive depletion of heavy isotopes from the Amazonian source (Insel, 2013; Apaéstegui et al., 2023; Vargas et al., 2022). However, analysis of ice cores extracted in 2019 reveals that, while the isotopic record ($\delta^{18}O$) at a regional scale responds to the climatic variability of the tropical Pacific (especially in the NINO3.4 region) and to El Niño-related teleconnections that modulate precipitation over the Amazon basin, at a local scale its variability is more determined by changes in atmospheric temperature than by precipitation itself. This distinction explains why, in contrast to the regional signal, precipitation and groundwater in lower-lying areas show greater variability and isotopic

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453 enrichment, suggesting a more direct influence of warmer temperatures (Vuille et al., 2003). Over
454 the past 60 years, the relationship between climate and $\delta^{18}O$ in these glaciological archives has
455 intensified in parallel with atmospheric and oceanic warming, as well as modifications in the
456 Walker circulation, demonstrating its sensitivity to recent climate change.
457 In Africa, data coverage is limited and largely restricted to liquid waters. Precipitation, streams,
458 and groundwater show relatively high $\delta^{18}O$ values, with medians generally between −10‰ and
459 −7‰. Africa is characterized by generally higher $\delta^{18}O$ and $\delta^{2}H$ values compared to high-latitude
460 regions, reflecting warmer temperatures and dominant convective rainfall regimes. Because
461 equilibrium fractionation decreases at higher temperatures, precipitation tends to be less
462 depleted in heavy isotopes, consistent with tropical hydroclimatic conditions (Gat & Matsui, 1991;
463 Rozanski et al., 1996). Moisture supplying high-mountain precipitation in East and Central Africa
464 is primarily derived from the Indian Ocean and regional continental recycling (Levin et al., 2009).
465 The limited representation related endmember reflects the scarcity of extensive cryosphere
466 environments across the continent and highlights the need for expanded isotopic sampling in
467 African mountain regions to better constrain hydrological responses to climate change.
468 Asia exhibits a broad isotopic range driven by strong topographic and climatic gradients.
469 Snowpack and glacier ice are particularly depleted in heavy isotopes, with median $\delta^{18}O$ values
470 typically between −15 and −12‰, showing high-elevation snowfall and intense Rayleigh
471 distillation over the Himalaya–Tibetan Plateau (Yao et al., 2013). Higher, colder mountains (like
472 the Himalaya–Tibetan Plateau) induce stronger Rayleigh distillation, resulting in more negative
473 $\delta^{18}O$ values. Glacial meltwater retains similarly low SWI values but with greater spread, while
474 streams and groundwater cluster around −12 to −9‰, consistent with mixing between ^{18}O-
475 depleted cryosphere sources and relatively ^{18}O-enriched monsoon precipitation (Immerzeel et al.,
476 2010). In some cases, the variability might arise from mixing with precipitation or snowmelt, or
477 from the selection of sampling sites, rather than intrinsic fluctuations in the glacier meltwater
478 itself. The pronounced variability in $\delta^{18}O$ values across endmembers is indicative of the region's
479 complex interplay between elevation, atmospheric circulation, and moisture sources. This
480 diversity is further illustrated by the wide interquartile ranges in the boxplots (Fig. 5), which
481 capture both the strong depletion in high-altitude environments and the enrichment associated
482 with lowland rainfall and groundwater recharge.
483 European waters show moderate ^{18}O-depletion and comparatively narrow interquartile ranges.
484 This is probably due to this very limited area of investigations (latitude limited data) with no data

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485 from northern EU. Glacier ice, streams, and groundwater typically fall between −12 and −8‰,
486 reflecting mid-latitude precipitation regimes, westerly moisture transport, and a weaker altitude
487 effect relative to high mountain regions (Rozanski et al., 1993; Stumpp et al., 2014). The reduced
488 variability in streams and groundwater highlights buffering and seasonal averaging, perhaps
489 stronger than other continents, which lower isotopic extremes and produce more stable
490 signatures over time. The relatively limited spread in $\delta^{18}O$ values across endmembers in this part
491 of Europe, as shown in Figure 5, suggests that regional hydrology is dominated by moderate
492 climatic gradients and efficient mixing of water sources, in contrast to the more pronounced
493 variability observed in Asia, Northa America and South America.
494 In Oceania, the available data are extremely limited, with only a single endmember represented
495 in the dataset. As a result, it is not possible to draw meaningful conclusions or interpret regional
496 isotopic patterns for this continent.
497 These continental patterns suggest the dominant controls on water isotope variability with
498 following evident: temperature and altitude effects driving heavy isotope depletion in cold and
499 high-elevation regions, atmospheric circulation shaping regional gradients, evaporation enriching
500 surface and near-surface waters with heavy isotopes in warm climates, and hydrological mixing
501 buffering isotopic extremes in streams and groundwater (Dansgaard, 1964; Rozanski et al., 1993;
502 Gat, 1996; Kendall & McDonnell, 1998; Gibson & Edwards, 2002).

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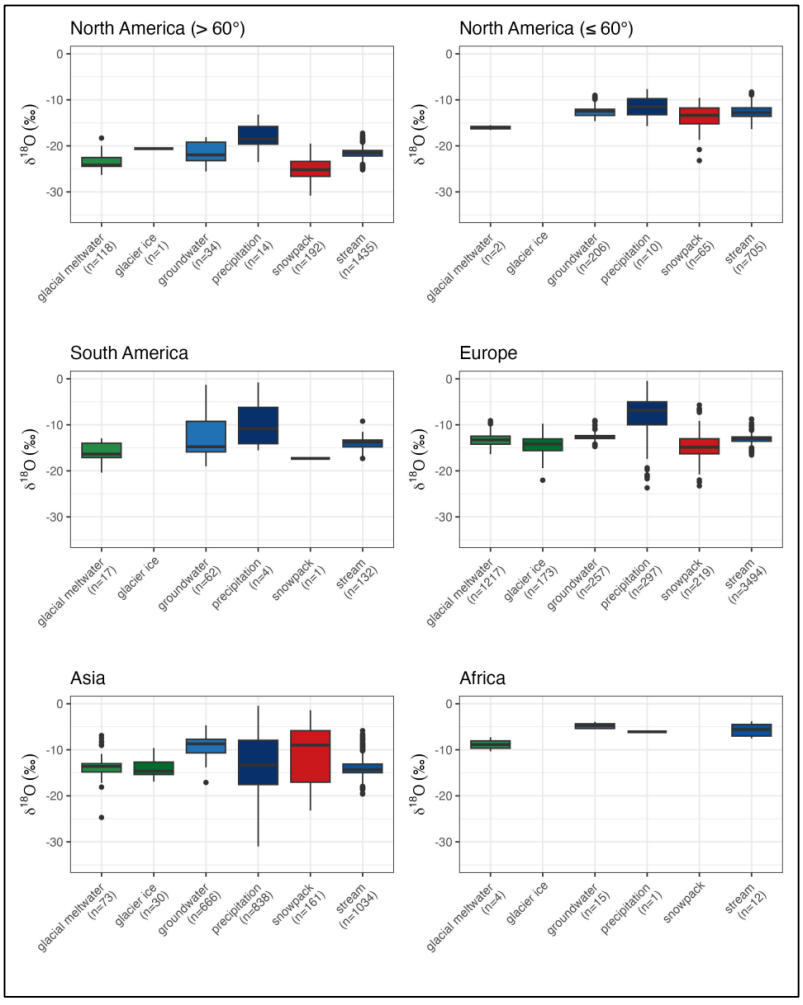

Figure 4. Continental-scale variability in δ¹⁸O (‰) for major hydrological and cryosphere endmembers across glacierized regions. Boxplots show regional distributions for North America (>60° and ≤60° latitude), South America, Europe, Asia, and Africa, illustrating differences in isotopic depletion related to latitude, elevation, and climatic setting. Sample sizes (n) are indicated for each endmember.

4.4. Deuterium excess and moisture source in hydrological and cryosphere endmembers

The d-excess distributions shown in Figure 5 show the moisture source conditions. Overall, most endmembers cluster around positive d-excess values (roughly 8–15‰), indicating that the primary precipitation isotopic signal is preserved across the dataset and that moisture sources

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were largely characterized by non-equilibrium conditions at the ocean–atmosphere interface. Low relative humidity, strong wind speeds, or cooler sea surface temperatures enhance kinetic fractionation during evaporation, increasing d-excess in the resulting vapor and, ultimately, in precipitation. Snowpack and glacier ice display the highest median d-excess values (typically ~14–18‰), consistent with cold-season precipitation and high-elevation snowfall, where kinetic fractionation during vapor formation and condensation enhances d-excess (Dansgaard, 1964; Pfahl & Sodemann, 2014). Cryosphere-derived meltwaters (supraglacial meltwater, glacial meltwater) show slightly lower and more variable d-excess. This suggests post-depositional modification during sublimation, melting, refreezing, and surface exposure, where partial evaporation and exchange with atmospheric moisture tend to reduce d-excess. Streams and groundwater occupy intermediate ranges, typically have d-excess of 10–12‰, consistent with the mixing of multiple sources and hydrological buffering that smooths variabilities (Kendall & McDonnell, 1998; Jasechko et al., 2014). Lakes, talus-slope, and ice-cored moraine waters exhibit lower median d-excess values and broader spreads, in some cases approaching or dropping below ~8‰. This pattern is indicative of evaporation under sub-saturated conditions. The relatively wide interquartile ranges in these open waters suggest variable residence times and differing degrees of evaporation (Gat, 1996; Gibson et al., 2008). Permafrost thaw waters show moderate d-excess values but with substantial scatter, highlighting their transitional nature between stored cryosphere ice and active hydrological endmember. Variability likely reflects heterogeneity in ice age, freezing history, and subsequent interaction with soil water during thaw (Yang et al., 2024).

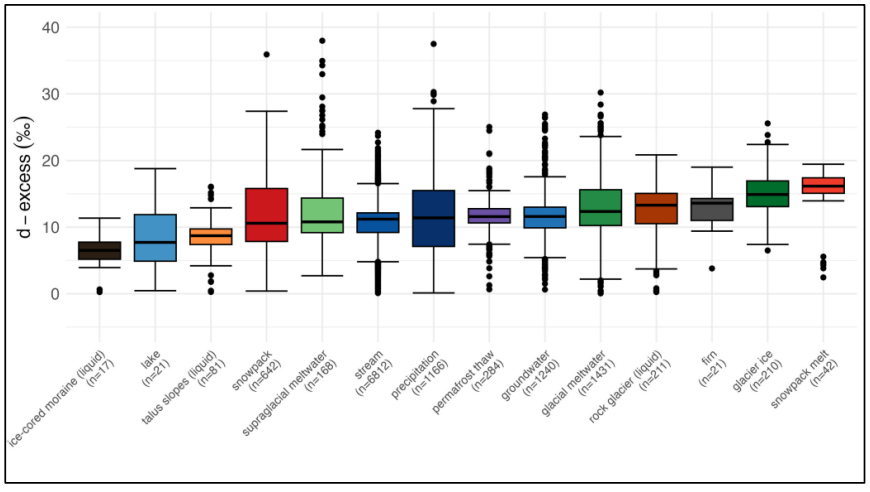

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Figure 5: Global distribution of d-excess (‰) across cryosphere and hydrological endmembers. Boxplots illustrate variability in d-excess values among liquid and solid water sources, including precipitation, stream, lakes, groundwater, snowpack, snowpack melt, glacial meltwater, supraglacial meltwater, firn, glacier ice, ice-core moraines, rock glacier, permafrost thaw, and talus slopes. Median values, interquartile ranges, and outliers highlight differences in moisture source conditions, evaporative processes, and secondary fractionation effects influencing isotopic signatures across glacierized catchments worldwide.

Figure 6 shows clear intercontinental differences in d-excess, reflecting variations in moisture source conditions, atmospheric transport pathways, precipitation seasonality, and post-depositional modification. Because d-excess is primarily established during oceanic evaporation, relative humidity and sea-surface temperature at the moisture source exert first-order control. Low relative humidity and strong kinetic fractionation at the interface generate higher d-excess, whereas evaporation under humid conditions produces lower values.

This is evident in Asia, where elevated median d-excess (>10‰) reflects a strong influence of moisture derived from relatively dry, cool oceanic sources. In parts of Central and Inner Asia, long transport pathways and cold-season snowfall further contribute to elevated d-excess in cryosphere components. Snowpack and glacier ice frequently preserve winter precipitation signals formed under lower humidity conditions, resulting in higher median values relative to groundwater and streams. In contrast, South America and lower-latitude regions of North America show lower median d-excess and broader distributions, consistent with a greater contribution from warm and humid tropical moisture sources and enhanced continental recycling during atmospheric transport (Chen et al., 2020; Kim et al., 2025). Continental recycling and sub-cloud evaporation reduces d-excess (Pfahl & Sodemann, 2014). In regions with long atmospheric transport pathways and strong continental recycling (e.g., parts of Asia and South America), precipitation can experience evaporation during descent or mixing with recycled moisture, increasing scatter and often lowering d-excess (Pfahl & Sodemann, 2014; Terzer-Wassmuth et al., 2021). At higher latitudes (>60°N), North America shows moderately elevated values, nevertheless, values remain lower than in some Asian regions, likely reflecting dominant Pacific moisture influence.

Europe shows intermediate to moderately high median d-excess values across most hydrological components, with relatively broad distributions, particularly in precipitation and glacier

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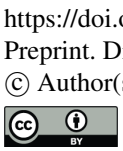

meltwater. This pattern reflects the superposition of multiple moisture sources and strong seasonal contrasts. Africa exhibits comparatively high median d-excess, particularly in groundwater and precipitation. This pattern is consistent with moisture derived from relatively dry source regions under low humidity. Under such conditions, kinetic effects during vapor formation enhance d-excess. However, the African dataset is limited in size and cryosphere representation, and precipitation and stream categories are sparsely sampled. The narrow distribution therefore likely reflects the scarcity of the dataset structure rather than a homogeneous continental signal. The elevated values should be interpreted cautiously.

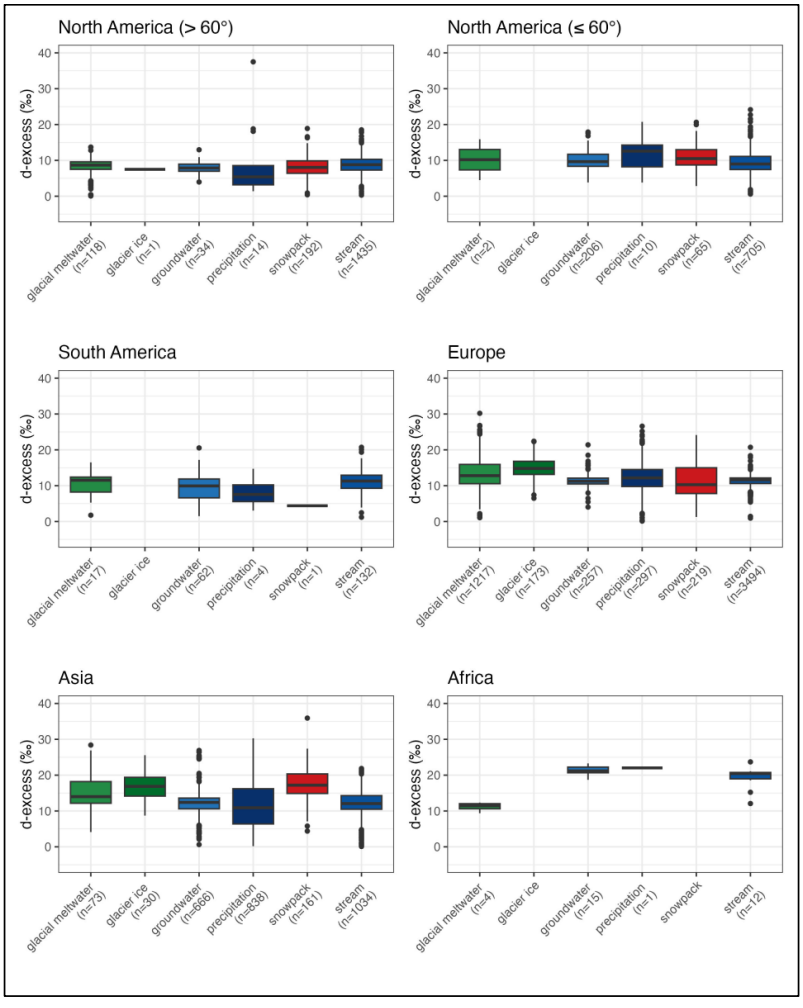

Figure 6: Continental-scale variability in d-excess (‰) across major cryosphere and hydrological

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endmembers. Boxplots illustrate regional distributions for North America (>60° and ≤60° latitude), South America, Europe, Asia, and Africa, highlighting differences in moisture source conditions, evaporation effects, and atmospheric processes influencing isotopic signatures. Variability among precipitation, snowpack, glacier-derived waters, groundwater, and streams reflect regional climatic gradients and mixing processes, with sample sizes (n) indicated for each endmember.

4.6. Implications for Isotope Hydrology in Glacierized catchments

Global and continental-scale pairwise statistical comparisons of $\delta^{18}O$ among major cryosphere and hydrological endmembers reveal clear differences in isotopic separation strength on the global scale and between regions, largely controlled by climatic gradients, moisture sources, and data availability (Figures S1 and S2 in supplementary Information). The post-hoc Dunn's test results indicate that most cryosphere and hydrological endmembers are statistically distinguishable based on their stable isotope compositions ($p < 0.05$), demonstrating a generally robust separation among major water sources. Precipitation exhibits statistically significant SWI differences ($p < 0.05$) from most other endmembers, including glacier ice, meltwaters, groundwater, lake, stream, indicating that its primary atmospheric signal is substantially modified during storage and transport within the catchment. In contrast, liquid endmembers display greater internal similarity and more frequent non-significant differences, consistent with rapid mixing and short residence times. Multiple cycles of melting and refreezing mean that the snowpack endmember varies to the point it is not significantly different from all other endmembers when considering the global dataset. Waters derived from rock glaciers, ice-cored moraines, and talus slopes remain significantly distinct, suggesting additional fractionation and storage effects.

Europe shows the strongest and most systematic statistical separation between endmembers. Most pairwise comparisons are highly significant ($p < 0.001$), indicating well-defined isotopic distinctions between precipitation, snowpack, glacial meltwater, groundwater, and streams. This likely reflects strong seasonal contrasts, elevation gradients in the Alps, and relatively dense datasets. Asia also exhibits widespread significant differences, although slightly less uniform than Europe. Strong contrasts between snowpack, precipitation, and groundwater suggest pronounced variability in moisture origin and secondary fractionation across High Mountain Asia. The influence of monsoonal inputs and continental recycling probably enhances d-excess variability, increasing separability among endmembers. North America (>60°) shows moderate

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differentiation. Significant contrasts mainly occur between glacial meltwater, precipitation, and stream water, whereas glacier ice itself appears less distinct, possibly reflecting overlapping moisture source conditions or limited sample numbers. In contrast, North America (≤60°) shows relatively few significant comparisons, implying greater mixing or weaker climatic gradients at mid-latitudes. South America presents limited statistical separation overall. Only a few comparisons involving stream water and glacial meltwater reach significance, which likely reflects smaller sample sizes and narrower $\delta^{18}O$ variability within Andean datasets. Similarly, Africa shows minimal significant contrasts; most cells are non-significant or unavailable, consistent with sparse cryosphere representation and limited sampling.

Overall, the analysis indicates that $\delta^{18}O$ is a powerful discriminator of hydrological endmembers in regions with strong atmospheric gradients and robust datasets (Europe, Asia), whereas in regions with limited cryosphere presence or smaller sample sizes (Africa, parts of South America), statistical differentiation remains weak. The important variability observed within endmembers such as snowpack, meltwaters, precipitation, and streams highlights the strong influence of local conditions and the timing of sampling. Also, precipitation is mostly sampled on a monthly time scale, but the variability of daily samples can be even greater (Saidaliyeva et al., 2024) while other components are mostly result of snapshot sampling campaigns. This variability makes clear that endmembers need to be defined with care (only use in analysis those endmembers that have a clear, significant separation from other) and that uncertainty should be explicitly considered when using isotopes for mixing analyses or hydrograph separation (Christophersen & Hooper, 1992; Barthold et al., 2011, Popp et al., 2025).

5. Conclusions and Applications

The preparation of the database (Vital et al., 2026) revealed several recurring gaps in how isotope data is reported, which reduce their usability for comparative analyses and modelling applications. In many studies, sampling locations are not described with sufficient spatial precision, with coordinates missing, rounded, or limited to general catchment descriptions. Information on analytical procedures is often incomplete, including the type of instrument used, calibration protocols, or reference standards, and analytical uncertainties are not always provided in a consistent way. Another common limitation is the reporting of isotope results only as averages or ranges, without access to individual sample values and sampling dates, which restricts

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the evaluation of temporal variability and uncertainty. Highlighting these issues and encouraging more complete metadata reporting would improve data transparency and facilitate the integration of future datasets into regional and global isotope compilations.

The studied spatial distribution of stable water isotopes in glacierized catchments provides a framework for interpreting endmember contributions and supports the application of isotope-based mixing approaches in glacierized and non-glacierized catchments worldwide. The dataset can be used as a baseline for multiple applications in hydrology, climate science, and water management. Particularly, isotope data can be applied in endmember mixing analysis to partition the streamflow into contributions from snowmelt, glacier melt, and groundwater. This is especially relevant in mountain catchments where seasonal water supply depends on cryosphere sources (Kendall & McDonnell, 1998). Additionally, ice cores preserve isotope signatures of past precipitation. By linking modern endmember isotopes with paleoclimate records, this dataset can support the reconstruction of past hydrological regimes and climate change (Rozanski et al., 1992). Finally, this dataset provides benchmarks for isotope-enabled hydrological models (e.g., iCESM, IsoHydro, JAMS200). The interpretations, presented here, of this unique global dataset are a beginning, and we believe that making these data available to the community will help facilitate more in-depth investigation of the key factors and processes determining the hydrology of glacierized catchments measured through water stable isotope ratios. Understanding temporal and spatial variations in the stable isotopic composition of cryosphere and hydrological components is essential and crucial for sustainable water resource management because of climate change, land use changes and human activities impact aquifer recharge, as well as surface and groundwater quality and quantity (Gačnik et al, 2026). Therefore, it is crucial to perform long-term isotope monitoring, continue with updating the database, to ensure the traceability of water isotope data, to provide results comparable in space and time, and to implement the FAIR data practice into daily research, following the goals of the Global Analysis laboratory Network (GloWAL) - IAEA.

Data availability

Data described in this manuscript can are publicly available through the ZENODO data repository. The dataset can be accessed at: https://doi.org/10.5281/zenodo.19062383.

Software

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675 The codes used in this study are available publicly available through the ZENODO data repository.
676 The codes can be accessed at: https://doi.org/10.5281/zenodo.18982251
677
678 **Author contributions**
679 Conceptualization (MV, YV, AW, JMD, AP, PV), data curation: (All authors), formal analysis (MV,
680 EJ, YV, AW, JMD, AP), funding acquisition (YV, MV), methodology (MV, YV), software (EJ),
681 supervision (MV, YV), validation: (MV, YV, AW, JMD, AP, PV), visualization (EJ, MV), writing –
682 original draft preparation (MV, YV, AW, JMD, AP,: MT, PV), writing – review and editing: All
683 authors.
684
685 **Competing interests**
686 The authors declare that they have no conflict of interest.
687
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699
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