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Recent Advances in Tracer-Aided Mixing Modeling of Water in the Critical Zone

Andrea L. Popp[1,2,3], Harsh Beria[4,5], Matthias Sprenger[6,7], Pertti Ala-Aho[8], Miriam Coenders-Gerrits[9], Jannis Groh[10,11,12], Julian Klaus[13], Julia L. A. Knapp[14], Gerbrand Koren[15], Iris Bakiri[16], Esther Xu Fei[17], Marina Gillon[18], Ciaran Harman[17,19], Christophe Hissler[20], Tegan Holmes[21], Ghulam Jeelani[22], Andis Kalvans[23], Alessandro Montemagno[20], Emel Zeray Öztürk[24], Petra Žvab Rožič[25], Tricia Stadnyk[21], Christine Stumpp[26], Nicolas Valiente[27], Jana von Freyberg[28,29], Polona Vreča[30], Giulia Zuecco[31,32], Ilja van Meerveld[33], Daniele Penna[34,35], and James W. Kirchner[4,29,36]

[1]Department of Geosciences, University of Oslo, Oslo, Norway, [2]Hydrological Research Unit, Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden, [3]Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden, [4]Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland, [5]WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland, [6]Lawrence Berkeley National Laboratory, Earth and Environmental Sciences Area, Berkeley, CA, USA, [7]Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC, USA, [8]Water, Energy and Environmental Engineering, University of Oulu, Oulu, Finland, [9]Department of Water Management, Delft University of Technology, Delft, The Netherlands, [10]Department Soil Science and Soil Ecology, Institute of Crop Science and Resource Conservation, University of Bonn, Bonn, Germany, [11]Agrosphere Institute (IBG-3), Forschungszentrum Jülich (FZJ), Jülich, Germany, [12]Isotope Biogeochemistry and Gas Fluxes, Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany, [13]Department of Geography, University of Bonn, Bonn, Germany, [14]Department of Earth Sciences, Durham University, Durham, UK, [15]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands, [16]Department of Instrumental Analytical Methods, University of Tirana, Tirana, Albania, [17]Department of Environmental Health and Engineering, Johns Hopkins University, Baltimore, MD, USA, [18]Mediterranean Environment and Agrohydrosystems Modelling, Avignon University, Avignon, France, [19]Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, MD, USA, [20]Catchment and Ecohydrology Research Group, Luxembourg Institute of Science and Technology, Belvaux, Luxembourg, [21]Department of Civil Engineering, University of Calgary, Calgary, AB, Canada, [22]Department of Earth Sciences, University of Kashmir, Srinagar, India, [23]Faculty of Geography and Earth Sciences, University of Latvia, Riga, Latvia, [24]Department of Geomatics Engineering, Konya Technical University, Konya, Turkey, [25]Department of Geology, Faculty of Natural Sciences and Engineering, University of Ljubljana, Ljubljana, Slovenia, [26]Department of Landscape, Water and Infrastructure, BOKU University, Institute of Soil Physics and Rural Water Management, Vienna, Austria, [27]Department of Science and Agroforestry Technology and Genetics, University of Castilla-La Mancha, Albacete, Spain, [28]School of Architecture, Civil and Environmental Engineering, EPFL, Lausanne, Switzerland, [29]Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland, [30]Department of Environmental Sciences, Jožef Stefan Institute, Ljubljana, Slovenia, [31]Department of Land, Environment, Agriculture and Forestry, University of Padova, Padova, Italy, [32]Department of Chemical Sciences, University of Padova, Padova, Italy, [33]Department of Geography, University of Zurich, Zurich, Switzerland, [34]Department of Agriculture, Food, Environment and Forestry, University of Florence, Florence-Firenze, Italy, [35]Forest Engineering Resources and Management Department, Oregon State University, Corvallis, OR, USA, [36]Department of Earth and Planetary Science, University of California, Berkeley, CA, USA

Andrea L. Popp and Harsh Beria contributed equally to this work.

Key Points:

- Tracer-aided mixing models are uniquely capable of identifying water flow paths and sources within the Critical Zone
- Recent advances offer novel tracers and models for deeper and more accurate insights into the Critical Zone
- Tracer and model-related uncertainties should be accounted for in model assessment

Supporting Information:

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

Correspondence to:

A. L. Popp and H. Beria,
andrea.popp@smhi.se;
hberia@ethz.ch

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Author Contributions:

Conceptualization: Andrea L. Popp, Harsh Beria, Matthias Sprenger, Pertti Ala-Aho, Miriam Coenders-Gerrits, Jannis Groh, Julian Klaus, Julia L. A. Knapp, Gerbrand Koren, Christine Stumpp, Giulia Zuecco, James W. Kirchner
Funding acquisition: Andrea L. Popp, Ilja van Meerveld, Daniele Penna
Methodology: Andrea L. Popp, Harsh Beria, Matthias Sprenger, Pertti Ala-Aho, Christophe Hissler, Ghulam Jeelani, Petra Žvab Rožič, Tricia Stadnyk, Christine Stumpp, Jana von Freyberg,

Abstract Safeguarding water resources for society and ecosystems requires a comprehensive understanding of hydrological fluxes within the Critical Zone, Earth's living skin where the atmosphere, hydrosphere, biosphere, and lithosphere meet. For decades, tracer-aided mixing models have been used to track water flow paths through the Critical Zone, mapping the journey of water particles from atmospheric moisture to groundwater. Recent advances in novel tracer measurements and modeling methodologies offer new insights into hydrological partitioning within the Critical Zone, enabling improved quantification of water fluxes across scales ranging from microscopic to macroscopic. Advanced tracer-aided modeling approaches enable more rigorous testing of assumptions and improved quantification of uncertainties. In this review, we (a) summarize state-of-the-art tracer and modeling techniques, with an emphasis on stable water isotope tracers, (b) synthesize insights emerging from new approaches, and (c) highlight opportunities to apply these methods in interdisciplinary Critical Zone research.

Plain Language Summary The Critical Zone is a dynamic interface where air, water, soil, plants, and rocks interact. Ensuring sustainable water resources and healthy ecosystems requires understanding how water

Ilja van Meerveld, Daniele Penna, James W. Kirchner
Project administration: Andrea L. Popp, Harsh Beria, Miriam Coenders-Gerrits, Christine Stumpp, Ilja van Meerveld, Daniele Penna, James W. Kirchner
Resources: Andrea L. Popp, Harsh Beria, Ilja van Meerveld, Daniele Penna
Supervision: Andrea L. Popp, Harsh Beria, James W. Kirchner
Visualization: Andrea L. Popp, Harsh Beria, James W. Kirchner
Writing – original draft: Andrea L. Popp, Harsh Beria, Matthias Sprenger, Pertti Ala-Aho, Miriam Coenders-Gerrits, Jannis Groh, Julia L. A. Knapp, Gerbrand Koren, Iris Bakiri, Esther Xu Fei, Ciaran Harman, Tegan Holmes, Andis Kalvans, Alessandro Montemagno, Petra Žvab Rožič, Tricia Stadnyk, Nicolas Valiente, Giulia Zuecco, James W. Kirchner
Writing – review & editing: Andrea L. Popp, Harsh Beria, Matthias Sprenger, Pertti Ala-Aho, Miriam Coenders-Gerrits, Jannis Groh, Julian Klaus, Julia L. A. Knapp, Gerbrand Koren, Iris Bakiri, Esther Xu Fei, Marina Gillon, Ciaran Harman, Christophe Hissler, Emel Zeray Öztürk, Jana von Freyberg, Polona Vreča, Ilja van Meerveld, Daniele Penna, James W. Kirchner

moves within the Critical Zone and how this may change in the future. To model water partitioning within the Critical Zone, researchers often use tracer-aided mixing models that allow us to track the movement of water using naturally occurring markers or "tracers." This approach quantifies the sources and flowpaths of water in the water cycle, from raindrops to aquifers deep below the ground. In this Review, we summarize the latest advancements in tracer-aided mixing models and how they help us to gain a clearer and more precise understanding of water pathways in the Critical Zone. In addition, we propose future research directions in this evolving field.

1. Introduction

Hydrological measurements and their subsequent modeling applications are widely used to quantify hydrological storages and fluxes. Tracers can provide additional insights into the path a water molecule takes through the Critical Zone (CZ) (e.g., Jasechko, 2019; Penna et al., 2018; Tetzlaff et al., 2015). "Conservative" (also called "passive") tracers interact minimally with their surrounding environment, and thus follow the water parcel that carries them. Conservative tracers thereby provide important constraints on flow paths and residence times within the CZ. Using tracer measurements combined with mass balance equations, mixing models can quantify the contributions of different water sources (typically called "end-members") to a water flux or compartment (typically called "mixture") (e.g., Barthold et al., 2011; Carrera et al., 2004; Cook & Dogramaci, 2019).

Tracer-aided mixing models (here also referred to as "mixing models") have been instrumental in advancing hydrology and related disciplines because they allow us to quantify the contribution of different water sources (e.g., snowmelt) to various hydrological compartments or fluxes (e.g., streamwater and groundwater). For example, mixing models can answer questions such as what proportion of streamflow originates from recent precipitation (vs. from groundwater stored within the catchment), and how this proportion changes as catchment wetness varies. Given the anticipated changes in the water cycle due to global warming and other environmental changes, answering such questions is crucial for protecting ecosystem functioning and sustainable water resource management.

Using naturally occurring tracers (so-called "environmental tracers") to infer hydrological processes through mixing models dates back to the 1950s (Begemann & Libby, 1957). This approach has revealed several previously unknown phenomena, such as that stormflow peaks are often dominated by water released from catchment storage, rather than recent rainwater that has rapidly reached the stream (e.g., Bishop et al., 2004; Kirchner, 2003). Another important discovery from the use of tracers is that, in certain landscapes, summer transpiration is predominantly supplied by winter precipitation, even when the bulk of annual rainfall occurs during summer (Allen, Kirchner, et al., 2019; Floriancic et al., 2024; Goldsmith et al., 2022). Environmental tracers have also been instrumental in quantifying fluxes to and through the CZ. For example, stable water isotopes have shown that groundwater recharge is often dominated by winter precipitation in temperate climates, and by intense rainfall in (semi-)arid climates (Jasechko et al., 2014; Jasechko & Taylor, 2015). Stable water isotopes have also suggested that in many landscapes, streamflow and tree water uptake originate from different water storages in the CZ (Brooks et al., 2010; Dawson & Ehleringer, 1991; Sprenger & Allen, 2020).

Mixing models have evolved from simple two- or three-component models (e.g., Johnson et al., 1969; Pinder & Jones, 1969; Sklash & Farvolden, 1979) (Figure 1), including the widely used "end-member mixing analysis" (EMMA) introduced by Christophersen et al. (1990) and Christophersen and Hooper (1992). These models are now advancing toward ensemble hydrograph separation (Kirchner, 2019) and Bayesian approaches, which allow for better characterization of uncertainties (e.g., Beria et al., 2020; Popp et al., 2019). Most modeling approaches require identifying all potential end-members, regardless of the number of tracers used. Typically, end-members are identified based on a conceptual understanding of the study site, aided by quantitative methods such as Principal Component Analysis, which assesses the minimum set of end-members required to explain the variability in the tracer signals of the water mixture (Christophersen & Hooper, 1992). In the next step, a mass-balance equation is used to estimate the mixing ratios for n end-members:

$$f_1 C_{1,k} + f_2 C_{2,k} + \ldots + f_n C_{n,k} = \sum_{i=1}^{n} f_i C_{i,k} = C_{m,k} \tag{1}$$

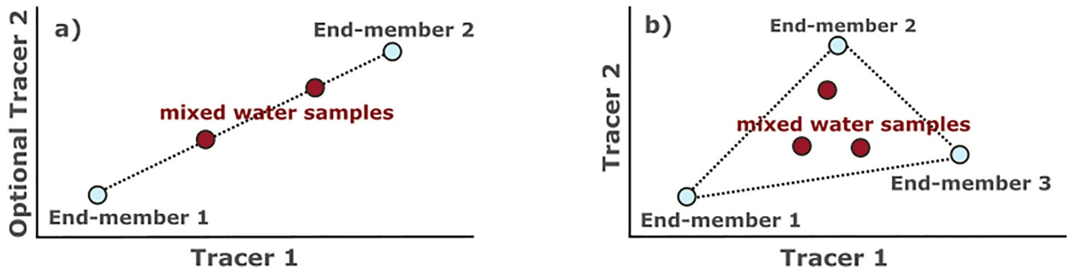

Figure 1. Simple example (with synthetic data) of end-member mixing with two (a) and three (b) end-members and two tracers (1 and 2). Blue circles denote tracer signatures of end-members, red circles denote signatures of mixtures. Note that example "a" could also be resolved with only one tracer.

where end-member i with tracer concentration $C_{i,k}$ of tracer k contributes a fraction $f_i \in [0,1]$ to the mixture concentration $C_{m,k}$. The fractional contribution of all end-members should sum to one:

$$f_1 + f_2 + \ldots + f_n = \sum_{i=1}^{n} f_i = 1 \quad (2)$$

Most traditional mixing models rely on several assumptions including: (a) the tracer signature of the mixture can be explained as a linear combination of the end-member signatures, (b) the tracers are conservative, meaning that any reactions that might alter the tracer concentrations in a mixture are much slower than the mixing process, (c) the tracer signatures of end-members are constant in time and space, (d) the end-members are sufficiently distinct from each other, and (e) all end-members are correctly identified. However, these assumptions are often violated in real-world applications, leading to substantial uncertainties in mixing model results (Carrera et al., 2004; Delsman et al., 2013; Hooper, 2003; Popp et al., 2019). Many of these assumptions can now be relaxed using novel mixing model approaches, as highlighted in this review.

Uncertainty in mixing ratios arising from space-time variability in tracer measurements is usually estimated using either linear error propagation (Genereux, 1998; Hooper et al., 1990; Uhlenbrook & Hoeg, 2003) or Monte Carlo methods (e.g., Bazemore et al., 1994; Durand & Torres, 1996). The temporal variability of a tracer at a specific location is often less than its spatial variability at a field site (Penna & van Meerveld, 2019), so spatial variability is often considered a more important source of uncertainty in mixing models (Iorgulescu et al., 2007; Joerin et al., 2002; Soulsby et al., 2003). The ability to constrain the mixing ratio depends on the size and composition of the tracer data set (Barthold et al., 2011; Popp et al., 2019), as well as uncertainties arising from field sampling, measurement procedures, and subsequent data analyses (see Box 1).

Box 1 Uncertainty Box

Tracer-aided mixing modeling requires a rigorous consideration of the associated uncertainties that arise from various sources, including the following:

- Spatial and temporal variability in hydrologic processes: Hydrological processes within the CZ are variable in space and time. Consequently, the scales at which studies are conducted will influence the outcomes. Spatial and temporal heterogeneity (e.g., caused by differences in subsurface properties or weather) combined with an insufficient sampling resolution can introduce scaling issues, making it challenging to generalize findings to larger scales or understand temporal patterns.
- Model uncertainty: The assumptions underlying a mixing model (e.g., concerning the number of end-members and linearity of mixing processes) will dictate its scope and limitations (Section 3).
- Laboratory uncertainties: Different instruments have different precision levels. Like field measurements, human or technical errors can distort the results, for instance, during calibration or post-processing of data. Accounting for such potential variations is important, particularly when working with data from other laboratories or when merging data from different sources.
- Non-unique source characterization: Different end-members can have similar tracer signatures (depending on the tracer used), which can result in difficulties distinguishing their contributions to a mixture. Some end-members may also be unmeasured, which complicates the interpretation of mixing model results.
- Tracer uncertainty: Each tracer's characteristics make it more suitable for some research questions than others (Section 2). The processes that control some tracer signals are still not fully understood. Resource constraints can also limit the scope of the available tracer data.
- Inconsistencies with data collection: Differing field sampling procedures, equipment calibration, or weather conditions, as well as human mistakes (e.g., accidental sample contamination) can introduce considerable uncertainties. The timing of sampling can also impact the results of mixing model analyses, particularly if samples are sporadic and infrequent.

Despite these limitations, tracers and mixing models remain essential tools for understanding water movement through the CZ, providing integrated signals over large areas that aid in inferring water mixing dynamics. This review has two main objectives. Firstly, we review recent advances in environmental tracers and mixing models. Secondly, we present improvements in process understanding arising from applications of mixing models to CZ research. The structure of this Review is as follows: Section 2 summarizes both conventional and novel tracers and tracer techniques; Section 3 outlines long-standing and recently developed mixing model approaches; Section 4 shows how recent advances in tracer and modeling techniques have led to new insights into transport, storage, and fate of waters in the CZ (Figure 2).

Due to the many advances in tracers and mixing models in recent years, it is necessary to limit the scope of this review. For example, we only include environmental tracers and exclude reactive tracers, and tracers that are not widely used (yet) or accessible, such as vanadium or eDNA. Similarly, we do not discuss reactive transport of solutes within the CZ, or transport and mixing in urban landscapes. We also do not address the integration of tracers into process-based hydrological and biogeochemical models, instead, we refer readers to the recent review by Jung et al. (2025) for a detailed discussion on this topic. Lastly, although transit-time modeling is equivalent to end-member mixing over continuous time, we exclude transit-time modeling from our review and refer to two recent reviews on this topic (Benettin et al., 2022; Sprenger, Stumpp, et al., 2019). Given the widespread use of stable water isotopes in CZ research, much of this review focuses on their application.

To enhance the readability of this review, Table S1 in Supporting Information S1 provides a glossary of specific terms as they are commonly understood in the field of hydrology.

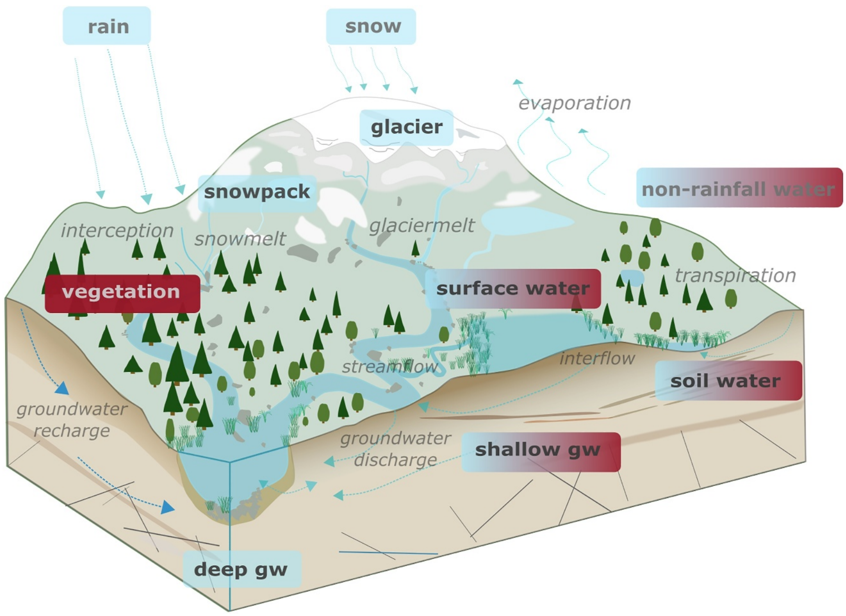

Figure 2. Conceptual model of the water compartments (boxes) and water fluxes (italic text) within the Critical Zone that are typically studied using tracer-aided mixing models. Light blue boxes indicate compartments that are considered to be end-members. Red boxes indicate compartments that are considered as mixtures. Boxes with both colors represent compartments that are either end-members or mixtures. "Gw" stands for groundwater.

2. Advances in Tracer Techniques

Here, we summarize tracers commonly used with mixing models for water source partitioning applications in the CZ (Table 1). Furthermore, we identify the typical temporal and spatial scales at which tracer aided mixing models are applied (Supplement Information of Table 1) and highlight novel tracers and tracer techniques that allow us to gain a better understanding of water exchange in the CZ (Table 1). Table 1 highlights relatively novel tracers in bold, while tracers that can be analyzed using recently developed techniques are shown in italics. We chose not to include tracers that have only been demonstrated in one or very few studies, as their usability has yet to be validated across a range of hydrological contexts. Therefore their broader applicability remains uncertain. In addition, analytical methods for these tracers are often not standardized or widely accessible to the broader research community.

Note that we only cover environmental tracers, which are substances that originate from the natural environment. Artificially added tracers, such as dye tracers (e.g., rhodamine, fluorescein, or uranine), salt tracers, or added gases (e.g., SF_6), are typically used to study water residence/travel times or biogeochemical turnover (e.g., Abbott et al., 2016; Sprenger, Stumpp, et al., 2019)—processes we do not cover in this review.

To enhance readability and comprehension, we have subdivided the various environmental tracers into groups. Tracers within one group share similarities, for example, the instruments or laboratory techniques that are needed for their measurement or the processes that they can help quantify (Supporting Information for Table 1). The tracer groups consist of (a) major elements, (b) trace elements, (c) noble gases, (d) radionuclides, (e) stable isotopes of water (also referred to as stable water isotopes), (f) derived isotopic signatures, (g) stable isotopes of major elements, (h) stable isotopes of trace elements, and (i) radiogenic isotopes of trace elements (Table 1).

Table 1 also contains the most common tracer species within these tracer groups and their main use within water compartments. Finally, we highlight advances, advantages and disadvantages of the different tracers, which are typically application-dependent. Mostly, advances and advantages are related to reduced costs, on-site analysis (vs. grab sampling and subsequent lab analysis), and smaller sample volume—all of which help to reduce uncertainty and facilitate high-resolution measurements to better understand the mixing dynamics within the CZ (e.g., Popp, Manning, & Knapp, 2021). Another factor is how conservative the tracers are. Some tracers, such as stable isotopes of water or noble gases, behave particularly conservatively in the saturated zone, which is key for

Table 1
Overview of the Types of Tracers That Are Typically Used in Tracer-Aided Mixing Modeling, Including Their Primary Applications, Advantages, and Disadvantages

Tracer group	Most common tracer species	Primary application	Advantages	Disadvantages
Major elements	Na^+, K^+, Mg^{2+}, Ca^{2+}, HCO_3^-, SO_4^{2-}, Cl^-, NO_3^-, Si	Atmospheric water, soil water, surface water, groundwater	Distinct signatures in many water sources, widely available, low-cost analytical methods	Non-conservative behavior
Trace elements	Sr, Ba, Mn, Zn, Cu, B, Li, Cr, Mo	Atmospheric water, soil water, surface water, groundwater	Widely available, low-cost analytical methods	Non-conservative behavior, low concentrations in natural waters
Noble gases	^{4}*Helium*, ^{222}*Radon*, $^{3}H/^{3}He$, ^{85}***Krypton***, ^{81}***Krypton***, ^{39}***Argon***	Groundwater	Very conservative behavior, new analytical tools allow for (in situ) high-resolution measurements	Difficult to sample, expensive with traditional analytical tools, limited analytical accessibility, potential for contamination
Radionuclides	Tritium (^{3}H)	Atmospheric water, surface water, groundwater	Part of the water molecule	High-uncertainties if used alone, costly
Stable isotopes of water	$\delta^{2}H$, $\delta^{18}O$, $\delta^{17}O$	Atmospheric water, plant water, soil water, surface water, groundwater	Ideal tracer for most water compartments, new analytical tools allow for (in situ) high-resolution measurements	Non-unique tracer signal among potential end-members
Derived isotopic signatures	**Deuterium-excess**, δ^{17}**O-excess**	Atmospheric water, soil water, surface water, groundwater	Provides constraints in addition to isotope measurements from which they are derived	Require measurement of multiple isotopic signatures, higher costs; no international standards available
Stable isotopes of other major elements	$\delta^{13}C$, $\delta^{34}S$, $\delta^{15}N$, δ^{44}**Ca**, δ^{26}**Mg**, δ^{30}**Si**	Atmospheric water, soil water, surface water, groundwater	Process specific	High-costs
Stable isotopes of trace elements	δ^{7}**Li**, δ^{11}**B**, δ^{138}**Ba**	Atmospheric water, soil water, surface water, groundwater	Distinctive among end-members	High analytical costs, often large sampling volume needed; potential for contamination
Radiogenic isotopes of trace elements	^{87}**Sr**/^{86}**Sr**, ^{206}**Pb**/^{207}**Pb**, ^{234}**U**/^{238}**U**, ^{143}**Nd**/^{144}**Nd**	Surface water, soil water, groundwater	No fractionation at any typically studied temporal scale	High costs, no widely available analytical technique

Note. Primary applications refers to the use of tracers both in characterizing end-members and in analyzing mixtures, as reflected in the literature. Novel tracers (i.e., tracers that recently became more widely available) are highlighted in bold; tracers that can be analyzed with techniques that have been recently developed are highlighted in italics. Tracers are assigned to groups based on their typical applications and analysis method.

reducing uncertainties in water source partitioning (e.g., Popp et al., 2019). Similarly, the most common disadvantages are related to high costs of labor and/or equipment, the lack of distinct signatures of end-members, and the fact that some tracers can currently only be analyzed by a few laboratories worldwide. The advantages and disadvantages summarized in Table 1 thus broadly govern the spatial and temporal applicability for each particular tracer. Note that when using "high/low" concentrations or costs, we speak in relative terms. The Table S1 in Supporting Information S1 further contains information on common analysis techniques for different tracer species as well as references including application examples.

Previous research studies (Barthold et al., 2011; Delsman et al., 2013; Popp et al., 2019) have shown that the number of different tracers, as well as the correct identification of end-members substantially influence the derived mixing ratios. Barthold et al. (2011) showed that including trace elements in addition to major elements can considerably reduce uncertainties and thereby lead to an improved understanding of water source partitioning in catchments. Popp et al. (2019) showed that a diverse set of conservative tracers exhibits the lowest uncertainties, while including non-conservative tracers such as nitrate and sulfate (which are still commonly used for mixing analyses) can considerably increase uncertainty (see Box 1 about uncertainties). These examples show that employing unsuitable tracers and disregarding underlying uncertainties can lead to a flawed interpretation of results and, thus, a potentially faulty understanding of hydrological processes. Generally, for a more robust approach, we advise using a combination of diverse tracers that exhibit different geochemical behavior while accounting for tracer-related uncertainties (Abbott et al., 2016; Popp et al., 2019; Tetzlaff et al., 2015). We refrain from providing general guidelines on which tracers to use for a specific research question, as this largely depends on the particular problem one aims to solve and available resources. For more detailed information on each particular tracer application, we refer to the respective references in Table S1 in Supporting Information S1 (see link provided in the Data Availability Statement section).

3. Advances in Tracer-Aided Mixing Models

The previous section summarized tracers that are commonly used in mixing models. This section focuses on recent advances in mixing models that employ these tracers to quantify water source partitioning within the CZ.

3.1. Hydrograph Separation Using EMMA

End-member mixing analysis (EMMA) is widely used to estimate the contributions of end-members to mixtures (Christophersen et al., 1990). In EMMA, the mixture combines the chemical and isotopic signatures of the end-members, which are assumed to mix conservatively, that is, without reacting with each other or with the media through which they travel (Hooper, 2003). Applications of EMMA typically (a) use Principal Component Analysis to reduce the dimensionality of the tracer data, (b) identify end-members that span the compositions of the mixture in principal component space, and (c) estimate the fractional contributions of the end-members to the mixture using matrix methods as described in Christophersen and Hooper (1992) and Barthold et al. (2011).

3.2. A GLUE-Based Approach to End-Member Mixing Analysis (G-EMMA)

EMMA explains tracer concentrations in a mixture in terms of tracer concentrations of end-members, and typically assumes that these end-member concentrations are invariant in space and time. Delsman et al. (2013), however, argue that observed tracer concentrations may not represent all potential end-members and that end-member concentrations may vary. Thus, they developed an approach that quantifies uncertainties in end-member identification, while allowing for overdetermined mixing models. Their approach is based on the generalized likelihood uncertainty estimation (GLUE) methodology (Beven & Binley, 1992) and is thus named G-EMMA. GLUE acknowledges equifinality (Beven, 2006), the often-observed phenomenon that the available observational data may be adequately explained by multiple sets of model parameters.

3.3. Convex Hull End-Member Mixing Analysis (CHEMMA)

In contrast to EMMA which requires the independent identification and sampling of end-members, Convex Hull End-Member Mixing Analysis (CHEMMA) infers the end-members (and their associated uncertainties) solely from the samples of the mixture (Xu Fei & Harman, 2022). Essentially, this "blind" decomposition of tracer data is achieved by fitting a simplex around the tracer data, where the corners of the simplex represent the tracer profiles of potential end-members. CHEMMA combines two machine learning methods, convex hull nonnegative matrix factorization (CH-NMF) and constrained K-means clustering (COP-KMEANS). Tight clusters indicate that the end-members can be robustly identified, while diffuse clusters suggest that the end-members cannot be adequately separated with the available data. Xu Fei and Harman (2022) tested this approach using streamflow isotope samples from the Panola data set and successfully identified the three end-members originally reported by Hooper et al. (1990). CHEMMA performed best when the mixture had contributions from all end-members, even if individual contributions were small, effectively exploring the boundaries of the mixing space.

3.4. Ensemble End-Member Mixing Analysis (EEMMA)

Conventional end-member mixing approaches require that all end-members have been sampled and that their mean tracer signatures are sufficiently distinct. The number of end-members also must not exceed the number of independent tracers, plus one. Where multiple sets of tracer measurements are available, however, these constraints can be relaxed by exploiting the information contained in correlations between fluctuations in the end-members and the mixture. This approach, termed Ensemble End-Member Mixing Analysis (EEMMA) (Kirchner, 2023) re-casts conventional end-member mixing problems as linear regressions, making several types of previously unsolvable problems mathematically tractable. For example, a single tracer can be sufficient to estimate the average mixing fractions of any number of end-members, even if their means overlap, as long as their fluctuations are sufficiently uncorrelated. One can also estimate mixing fractions for an incomplete set of end-members (or even just a single end-member), as long as their fluctuations are not too strongly correlated with any unmeasured end-members. It is even possible to estimate the time series of the weighted average of those missing end-member(s), if they are sufficiently uncorrelated with the measured end-members. To date, the potential of this new method has been demonstrated with synthetic benchmark data (Kirchner, 2023).

3.5. Bayesian End-Member Mixing Approaches

Bayesian mixing models (Parnell et al., 2010) have recently been applied in hydrology to estimate components of groundwater recharge (Beria et al., 2020; Popp, Pardo-Alvarez, et al., 2021; Popp et al., 2019), streamflow (Birkel et al., 2021; He et al., 2020; Miller et al., 2021) and root water uptake (Couvreur et al., 2020; Evaristo & McDonnell, 2017), among others. Bayesian mixing methods estimate the probability density function (pdf) of the mixing ratio, thereby offering a robust way to estimate uncertainty in water partitioning studies.

Broadly, two approaches are prevalent in Bayesian mixing analysis. In the first approach, pdfs are fitted to the tracer concentrations in different end-members (e.g., rainfall, snowfall) and the mixture (e.g., groundwater, streamwater). The pdf of the mixing ratio is estimated using standard Bayesian inference principles. If the pdfs that are fitted to the end-member and mixture tracers follow standard statistical distributions (e.g., Gaussians), the mixing ratio pdf can be inferred analytically (Stock et al., 2018). In other cases, the mixing ratio pdf is estimated by an optimization routine that seeks the best fit between the observed and simulated mixture tracers, through an iterative improvement of an initial guess of the mixing ratio distribution (Birkel et al., 2021; He et al., 2020; Popp et al., 2019). Recent advances in probabilistic programming languages have greatly simplified these optimization tasks (e.g., Carpenter et al., 2017).

Bayesian approaches typically require a large tracer data set to robustly fit the pdf. Tracer measurements are often scarce, particularly for potential end-members (Penna & van Meerveld, 2019). In such cases, a bootstrap approach can be used employing all possible combinations of end-member tracer measurements and a given distribution of mixing ratios to simulate mixture tracer concentrations. In this case, a likelihood function is formulated based on an assumed pdf of the underlying error function, which is the difference between simulated and observed target mixture concentrations (Beria et al., 2020). Therefore, this approach does not require fitting pdfs to the tracer compositions of different end-members. By using all available combinations of end-member concentrations, the method builds an empirical pdf while optimizing the likelihood function. This approach has been shown to work both theoretically and in real-case scenarios (Figure 3). In addition, this Bayesian approach can be combined with other EMMA-based methods that provide potential end-member suggestions. For example, CHEMMA's output of potential end-members can be used as a prior distribution of potential end-members.

3.6. Ensemble Hydrograph Separation

In contrast to conventional end-member mixing analyses, which are based on mass balances, ensemble hydrograph separation (Kirchner, 2019) is based on correlations between fluctuations in input and output tracer time

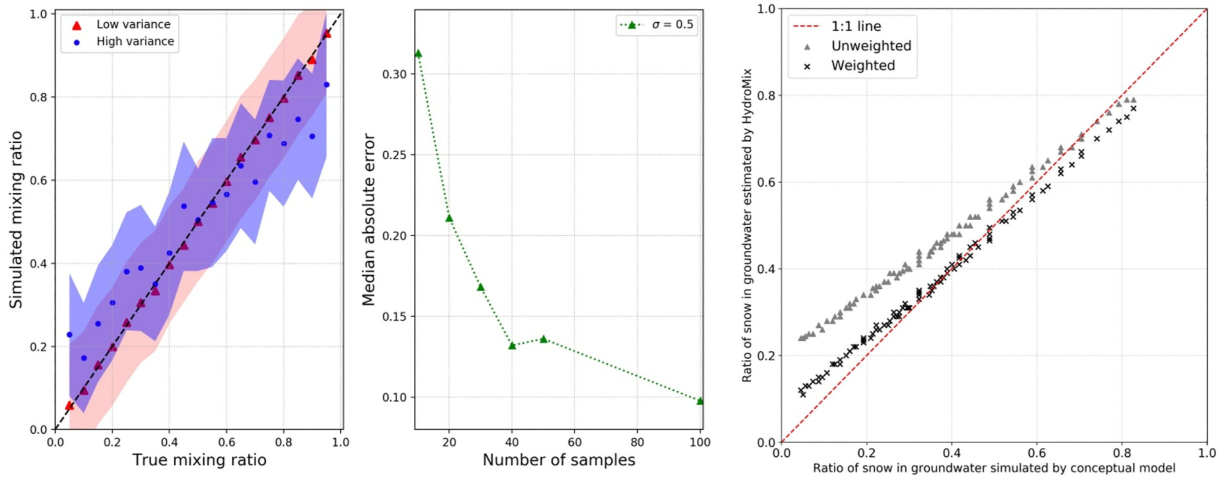

Figure 3. Figure benchmarking a Bayesian mixing model (HydroMix) using a synthetic data set and a conceptual hydrological model. (a) HydroMix-inferred mixing ratios closely match theoretical mixing ratios in low-variance data sets, while higher variance leads to greater deviations. The uncertainty band represents one standard deviation around inferred mixing ratio values. (b) Median absolute errors reduce with increasing sample size. (c) Ratios of snow in groundwater estimated using HydroMix are plotted against theoretical values of snow in groundwater obtained from a conceptual hydrological model, showing that flux-weighted mixing results in more accurate mixing. Figure adapted from Beria et al. (2020).

series. These correlations yield estimates of the new water fraction F_{new}, averaged over ensembles of either precipitation or discharge time steps. The method does not require continuous time series, so subsets of the data can be selected to reflect conditions of particular interest, such as wet versus dry antecedent conditions or high-intensity versus low-intensity precipitation. Thus catchment response to precipitation can be mapped out, directly from data, as a function of ambient conditions and external forcing. The "new" in F_{new} refers to precipitation that has fallen since the previous streamflow tracer sample. Thus, weekly sampling yields weekly new water fractions, daily sampling yields daily new water fractions, and so forth. This approach has successfully been applied by others (e.g., Burt et al., 2023; Floriancic et al., 2024; Knapp et al., 2019), and scripts are available to implement the approach (Kirchner & Knapp, 2020).

Because ensemble hydrograph separation is based on correlations rather than mass balances, it does not need to assume that end-member tracer signatures are constant (instead, it exploits their fluctuations). For the same reason (and in contrast to conventional end-member mixing methods), ensemble hydrograph separation does not need to assume that all potential end-members have been identified and measured; it must only assume that tracer fluctuations in any unmeasured end-members are not strongly correlated with those in the measured end-members. Ensemble hydrograph separation can also easily accommodate cases in which the end-member tracer concentrations overlap with each other; these cases simply have little leverage on the solution, whereas they lead to mathematical blowups in conventional end-member mixing. The ensemble hydrograph separation approach can be extended to multiple time lags, yielding estimates of transit time distributions (Kirchner, 2019), but these are beyond the scope of this review. This approach can potentially be extended beyond catchments to quantify the coupling between inputs and outputs in other systems as well.

3.7. End-Member Splitting Approach

Most of this review is concerned with interpreting CZ compartments (e.g., soil water, groundwater, xylem water, or streamwater) as mixtures of end-members (i.e., end-member mixing analysis; Figure 2). Often, it would be useful to know not only how end-members are combined in mixtures, but also how individual end-members are partitioned among their possible fates. This latter question is the domain of end-member splitting analysis (Kirchner & Allen, 2020), which combines isotope tracers and water flux measurements to estimate how isotopically distinct end-members (such as summer vs. winter precipitation) are partitioned among their different ultimate outputs (such as evapotranspiration or streamflow).

End-member splitting is derived from combining end-member mixing and isotope mass balance methods. Thus, all of the conventional assumptions of end-member mixing apply here, including (a) that the measured mixtures are derived entirely from only two end-members (or $n + 1$ end-members if we have n non-redundant tracers), (b) that the end-member tracer measurements are unbiased, and (c) that the tracer signatures of the mixtures are not affected by any fractionation that was not also present in the end-members. In addition, end-member splitting also requires that the sampled mixture(s) comprise all the outputs from the system except one, and that the water fluxes in these sampled mixtures, and the end-members, can be quantified with sufficient accuracy. Scripts are publicly available that perform all the necessary calculations, including error propagation (Kirchner, 2020).

4. Application: Insights on Temporal and Spatial Variability of Water Fluxes Within Different Critical Zone Compartments

This section highlights recent applications of tracer-aided mixing modeling approaches within specific compartments of the Critical Zone. The compartments we address are (a) atmospheric and frozen water (Section 4.1), (b) surface water (Section 4.2), (c) soil water (Section 4.3), (d) plant water (Section 4.4), and (e) groundwater (Section 4.5). For each of these compartments, we first identify the major end-members (except in the case of atmospheric water and frozen water, which are primarily considered as end-members themselves). We then describe how each compartment is typically sampled in time and space, and outline how its relevant hydrological processes have been elucidated through the application of mixing models.

4.1. Atmospheric and Frozen Water

4.1.1. Precipitation: Rainfall and Snowfall

Rainfall and snowfall collectively constitute the majority of global precipitation. Several naturally occurring tracers have been used to characterize rainfall and snowfall as end-members in mixing analyses. Among these, stable isotopes of water are the most commonly used (Table 1). Stable water isotopes have also been used to quantify the contribution of recycled moisture to precipitation (Froehlich et al., 2008). For example, in the semi-arid Heihe River Basin in China, a three-component isotopic mixing model revealed that 25%–50% of growing-season precipitation originated from local moisture recycling, primarily driven from transpiration (Zhao et al., 2019).

Mixing studies frequently require estimating average tracer signatures in both rainfall and snowfall, ideally accounting for their spatial and temporal variability. Capturing this variability necessitates extensive sampling to obtain representative end-member tracer signatures (Fischer et al., 2017).

Rainfall and snowfall samples are usually collected at fixed time intervals or as time-integrated samples after precipitation events. The sampling frequency varies depending on the research objectives and site accessibility. It can be relatively high, based on fixed time intervals, for example, 30-min collection intervals (von Freyberg et al., 2017) or fixed volumes, for example, 5 mm collection intervals (Cayuela et al., 2018), to study streamflow dynamics during storm events. Alternatively, for studies focusing on seasonal catchment dynamics, biweekly or monthly sampling campaigns may be sufficient (Michelon et al., 2023). Although data requirements regarding the length and frequency of measurements are rarely specified in the literature, Putman et al. (2019) suggests that at least 48 months of monthly precipitation isotope measurements are necessary to adequately characterize the long-term distribution of stable isotopes of water at a given site. Precipitation sampling networks should ideally be designed to be spatially representative (Hatvani et al., 2021). However, they are typically based on existing meteorological stations within larger international data collection networks (Stumpp et al., 2014; Vreča et al., 2022). In mountainous terrain, valleys and lowlands are often over-sampled relative to higher-elevation locations due to logistical constraints. When sampling is not feasible, precipitation tracers can sometimes be inferred from publicly available monitoring programs and databases, such as the Global Network of Isotopes in Precipitation (GNIP), or estimated using models such as isoscape interpolations (e.g., Allen et al., 2018; Nelson et al., 2021).

4.1.2. Non-Rainfall Water (NRW)

Non-rainfall water (NRW, comprising all water inputs in addition to rain or snow) can account for 5%–40% of annual precipitation in some regions (Aguirre-Gutiérrez et al., 2019; Groh et al., 2019; Lekouch et al., 2012).

NRW includes dew (e.g., Forstner et al., 2021; Kaseke, Mills, Brown, et al., 2012), fog (e.g., Breuer et al., 2021), frost (e.g., Feher et al., 2021; Groh et al., 2018), rime ice (e.g., Meissner et al., 2007), and water vapor adsorption to soils (e.g., Agam & Berliner, 2006; Saaltink et al., 2020). The composition of the NRW tracer varies temporally and spatially, depending on meteorological factors (Groh et al., 2018; Ritter et al., 2019), moisture sources (Kaseke et al., 2017), soil properties (Kaseke, Mills, Esler, et al., 2012), landscape position (e.g., Uclés et al., 2015), and vegetation characteristics (e.g., Malik et al., 2015). Inputs from NRW are frequently overlooked in end-member mixing studies, potentially amplifying uncertainties in mixing estimates. Although NRW generally accounts for a small proportion of daily precipitation (Zhuang et al., 2021), it can play a significant role in specific hydrological processes (Chung et al., 2017; Runyan et al., 2019), such as vegetation water uptake ((Zhuang et al., 2021), see Section 4.4) and soil recharge (see Section 4.3).

Only a few applications of mixing models have been made to understand the impact of NRW on ecohydrological processes. Dawson (1998) was one of the first to use water isotopes to show the significant role of fog in tree water uptake, demonstrating that fog water inputs to several California redwood trees accounted for 13%–45% of their annual transpiration. X.-F. Wen et al. (2012) showed that the stable isotopic composition of the dew water is significantly correlated with leaf water in a Chinese grassland site, indicating significant leaf water uptake at night. Li et al. (2021) used water isotopes to estimate the contribution of dew and fog to plant water uptake in a Swiss grassland and highlighted the importance of plant water uptake through soil distillation. Tian et al. (2021) showed that nighttime evaporation during heavy dew events was primarily driven by changes in relative humidity in three different climates: the arid central Namib Desert, Mediterranean Nice (France), and humid Indianapolis (USA). Using ^{17}O-excess alongside ^{2}H and ^{18}O, the study detected evaporation during dew formation in the Namib Desert and in Indianapolis when temperatures exceeded 14.7°C; however, dew in the Mediterranean climate of Nice showed minimal evaporation.

4.1.3. Snowpack and Glaciers

Precipitation can be stored above the ground surface for time scales varying from a few hours in forest canopies to several months in snowpacks, and even decades to millennia in glaciers and ice sheets. During above-ground storage, tracer concentrations can change considerably. For example, changes in the water isotopes have been documented in seasonal snowpacks (e.g., Noor et al., 2023; Rücker et al., 2019; Taylor et al., 2001) and during canopy interception (Allen et al., 2016; von Freyberg et al., 2019; Cayuela et al., 2018). In the following, we summarize how tracers can quantify the contributions of snow and glacier melt to hydrological processes in cold regions.

4.1.3.1. Seasonal Snow

In snow-dominated regions, water input to the CZ includes rainfall, snowmelt, and potentially glacial melt. The tracer composition of the snowmelt end-member can be estimated from samples of snowfall, snowpacks, or snowmelt, or numerical snowmelt models based on snowfall and snowpack measurements (Beria et al., 2018).

The variability in tracer composition generally decreases from snowfall to snowpack and snowmelt (Beria et al., 2018). However, due to the heterogeneity in snow accumulation and melt processes, tracer measurements in snow can exhibit high spatial variability, even over short distances (R. W. H. Carroll, Deems, Sprenger, et al., 2022; Hürkamp et al., 2018). Characterizing the tracer variability in seasonal snowpacks thus requires extensive sampling across the landscape. Snowmelt varies over time, and it is unclear which phase of melt (e.g., early, peak, or late) best characterizes the snowmelt end-member. Recently, Noor et al. (2023) revealed potential sublimation biases in tracer signals during early snowmelt in the Finnish Laplands, and recommended more frequent sampling during peak melt periods.

Snowpack sampling typically involves coring or excavating snow pits. In some cases, the entire snowpack, from top to bottom, is integrated into one sample (e.g., Ceperley et al., 2020; Penna et al., 2017; Rodhe, 1981). Alternatively, individual layers within the snowpack can be separately sampled (e.g., Ala-aho et al., 2021; R. W. H. Carroll, Deems, Sprenger, et al., 2022; Taylor et al., 2001). Snowpack tracers typically vary both vertically and laterally. Vertical variations often reflect the accumulated sequence of snowstorms and their tracer signatures, as modified by canopy interception, wind-driven snow redistribution, sublimation, snow metamorphism, and vapor exchange with ambient air (e.g., Feng et al., 2002; von Freyberg et al., 2019; Koeniger et al., 2008; Taylor et al., 2001). Lateral variations in snowpack reflect topographic influences (e.g., Beria et al., 2018; R. W. H. Carroll, Deems, Maxwell, et al., 2022; Dietermann & Weiler, 2013), in addition to the factors mentioned above. Snowmelt is often collected at regular intervals using lysimeters or passive capillary samplers (e.g., Laudon et al., 2002; Nehemy et al., 2022; Penna et al., 2014; Thaw et al., 2021), or sampled on an ad-hoc "grab sample" basis, directly from the base of a melting snowpack (e.g., Beria et al., 2018; Miller et al., 2021; Penna et al., 2016). Fractionation during melting and subsequent refreezing within the snowpack results in meltwaters being isotopically lighter than the bulk snowpack early in the melt season, becoming isotopically heavier than the bulk snow as the melt season progresses (Taylor et al., 2001). This underscores the importance of timing in snowmelt sampling and highlights the need for guidelines to sample snowmelt.

The snowmelt tracer composition can also be estimated via numerical modeling. There are currently two prominent modeling paradigms. The first approach simulates changes in snowpack tracer composition resulting from snow metamorphism and liquid-ice interaction along a vertical snowpack column. These models can also account for changes in tracers induced by atmospheric exchanges, such as the deposition of water vapor on the snowpack or snow mass loss via sublimation (e.g., Feng et al., 2002; Pu et al., 2020). The second approach uses mass balance models and assumes a uniform snowpack tracer composition, thereby simplifying tracer changes due to snow metamorphism (Ceperley et al., 2020; Stadnyk et al., 2013). This approach can simulate the spatial variability in snowmelt tracer compositions over large regions, without the exhaustive input data required by vertically-resolved snowmelt tracer models (Ala-aho et al., 2017; R. W. H. Carroll, Deems, Sprenger, et al., 2022). Modeling studies have revealed significant uncertainty in estimated snowpack contributions to streamflow, arising from the highly variable and dynamic nature of the melt.

4.1.3.2. Glaciers

Glaciers accumulate precipitation over periods ranging from years to millennia. Glacial ice preserves the tracer composition of precipitation at the time of its initial formation, serving as a valuable proxy record of past climates. However, post-depositional snow processes can modify the original precipitation water isotope signal, complicating the interpretation of ice core climate records (Dietrich et al., 2023). Glacial meltwater streams contain a mixture of ice melt from the glacier itself, rain falling on the ice surface, and snowmelt from snowpacks atop the glacier. From the onset of the snow ablation season, the tracer composition of glacial meltwater streams will change as melting progresses toward higher elevations, reflecting shifting contributions of snowmelt, rainfall, and ice melt, as well as altitude gradients in precipitation tracers preserved in the snow and ice. Capturing these seasonal dynamics requires frequent sampling campaigns, especially during the ablation season (Engel et al., 2015; Zuecco et al., 2019).

Water isotopes are frequently used to quantify runoff contributions from the melting of glacier ice (Liu et al., 2015; Ohlanders et al., 2013; Pu et al., 2017) due to the distinct signature of glacial melt compared to summer rainfall and groundwater. To distinguish tracer signatures of snowmelt from glacier melt in glacial meltwater streams, researchers have separately sampled snowmelt from glacier-free areas (Dietermann & Weiler, 2013; Schmieder et al., 2018) and sampled meltwater after seasonal snowpacks have melted out (Müller et al., 2022). There can be isotopic differences between glaciers and the snow from which they originate, due to isotopic fractionation during snow-firn metamorphism (Beria et al., 2018). However, stable isotopes of water often cannot be used to distinguish between glacial melt and snowmelt, because they frequently exhibit similar isotopic compositions (Zuecco et al., 2019). Differentiating glacial melt from snowmelt may therefore require multiple tracers, potentially including dissolved iron (Bhatia et al., 2013) or electrical conductivity (Penna et al., 2017; Rai et al., 2019).

As glaciers are often located in remote areas, they pose considerable logistical constraints, making it challenging to collect long-term tracer data at high spatio-temporal resolutions. Consequently, accurate characterization of the glacier end-member, a critical aspect for mixing models in glacierized catchments, is often compromised (He et al., 2021; Schmieder et al., 2018; Zuecco et al., 2019). These limitations highlight the need for new data collection approaches for remote glacial environments, to facilitate more robust and comprehensive assessments of runoff dynamics in cold regions.

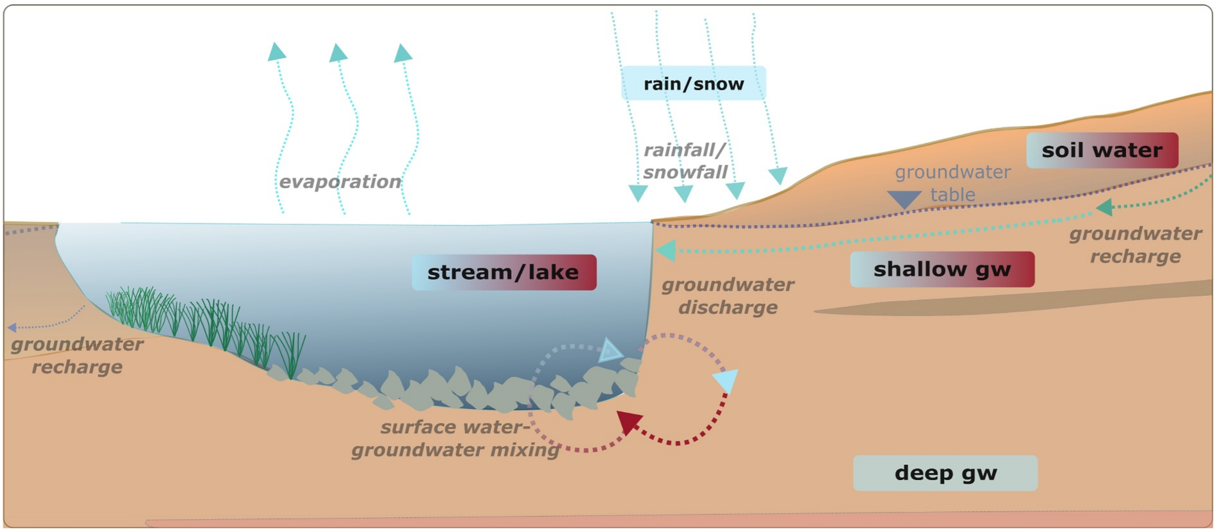

Figure 4. Water mixing processes in surface waters and groundwaters (gw) are typically studied using tracer-aided mixing approaches. Typical end-members are illustrated in blue. Water compartments that are considered as end-members or mixtures, depending on the study, are shown in blue (end-member) and red (mixtures).

4.2. Surface Water

4.2.1. Streamwater

4.2.1.1. Streamwater and Its End-Members in Time and Space

Quantifying the contributions of different end-members to streamflow is a common task in hydrology. Streamflow is generally a mixture of precipitation, soil water and groundwater, and depending on the specific catchment, can also include other fluxes such as snow and glacier meltwater, irrigation water, and leakage from water supply infrastructure. Since the 1960s, hydrologists have used tracer measurements and mixing models to determine the contributions of different end-members to streamflow and their variations through time (Gat & Tzur, 1967) (Figure 4).

The contributions of individual end-members can be quantified if their tracer concentrations are sufficiently distinct (Burns et al., 2001; James & Roulet, 2006; Soulsby et al., 2003). Depending on the available tracer measurements, it may also be possible to further differentiate individual end-members, for example, by distinguishing individual soil layers based on their geochemical tracer signatures (Hooper et al., 1990). In addition to quantifying the contributions of spatially distinct end-members, tracers are also widely used to distinguish contributions from waters of different ages, such as recent precipitation, snowmelt or glacier melt, as distinct from older soil waters or groundwaters (Sprenger, Stumpp, et al., 2019). Typical hydrograph separation studies use conservative tracers such as stable water isotopes to separate stormflow following precipitation events into "event water" (from the recent precipitation itself) and "pre-event water" stored within the catchment from previous precipitation inputs (Buttle, 1994; Klaus & McDonnell, 2013; Leibundgut et al., 2009).

Over time, approaches have emerged that blur the distinction between temporal and spatial hydrograph separation. Earlier studies contrasted the contributions of groundwater and direct runoff to streamflow (e.g., Pinder & Jones, 1969; Sklash & Farvolden, 1979). More recent studies have separated pre-event water into groundwater and soil water (McHale et al., 2002) or assessed contributions from different landscape units (e.g., riparian vs. hillslope zones) (McGlynn & McDonnell, 2003).

4.2.1.2. Sampling Streamwater and Its End-Members in Time and Space

Surface water sampled at the outlet of a catchment integrates hydrological processes within the catchment, making tracer signals useful for understanding spatially integrated water storage and release dynamics at the catchment scale. Characterizing and identifying potential end-members often requires comprehensive spatial sampling of both isotopic and geochemical tracers (see Table 1) in distinct catchment areas, such as riparian zones and hillslopes (e.g., James & Roulet, 2006).

The number of end-members required to explain streamflow tracer variability can depend on the timeframe of the research question. For instance, in a study of nested forested catchments in Canada, James and Roulet (2006) found that two distinct groundwater end-members, each with different average residence times, were essential to capture streamflow tracer variability at a seasonal scale. However, for the timescale of a single storm event, a single well-mixed groundwater end-member was sufficient. Hydrograph separation studies typically estimate the composition of pre-event water by sampling streamflow during baseflow conditions before the storm event (Sklash & Farvolden, 1979), and the composition of event water by sampling rainfall at one or several locations during the storm (McDonnell et al., 1991). However, the unequivocal identification of potential end-members is challenging due to their substantial spatial and temporal variability (Burns & McDonnell, 1998; Fischer et al., 2017; Kiewiet et al., 2019; Uhlenbrook et al., 2002). Quantifying how end-member contributions change within individual storm events often requires high-frequency streamflow sampling (Michel et al., 2020; von Freyberg et al., 2017), particularly in small and flashy headwater streams. Furthermore, spatial variations in precipitation, such as altitude effects in isotopic tracers, pose further challenges (Section 4.1).

4.2.1.3. Streamwater: Mixing Model Applications

Mixing models have been instrumental in advancing our understanding of water storage and release processes in diverse landscapes (Ceperley et al., 2020; Klaus & McDonnell, 2013). For instance, it has been widely observed that pre-event waters stored within a catchment are the primary contributors to streamflow during storm events, rather than the event precipitation itself. This phenomenon has been reported across diverse environments, including croplands, forests, and peatlands (Bishop et al., 2004; Burns et al., 2001; Gracz et al., 2015; Kirchner, 2003; Sklash et al., 1976). Mixing models have also been used to identify dominant water flow pathways in different landscapes (Durand & Torres, 1996). For example, in an agricultural catchment in Scotland, Soulsby et al. (2003) used tracers to show that overland flow predominantly occurs only during the peak of a storm, and subsurface flow pathways contribute the majority of streamwater recharge. While most mixing model studies quantify streamflow contributions from predefined end-members, Kirchner (2023) recently demonstrated that this approach can also be used to identify missing, unknown, or unsampled end-members.

Mixing models have also been proven to be useful in diverse environments including peatlands: Gracz et al. (2015) have shown that pore waters stored in the near-surface of Alaskan peatlands sustain streamflow during dry periods. This ability to regulate streamflow has been attributed to the buffering capacity of peatlands, which helps maintain stable water tables even under varying snowmelt conditions in Banff National Park, where groundwater contributes up to 53% of the water budget (Mercer, 2018). Interestingly, a semi-arid peatland in Chile has even exhibited a reverse water flow, where water moves from streams into the peatland, contrary to the more typical flow from peat-bearing soils to streams (Valois et al., 2021). These insights have significantly improved our understanding of peatland hydrology and its complex interactions with streamflow dynamics.

Mixing analyses have also been used to identify the seasonal sources of streamflow. For example, in the Willamette Basin in Oregon, during winters, river water is primarily recharged by precipitation falling in low mountains and valley bottoms, whereas during summers, the majority (60%–80%) of river flows are derived from snowmelt at higher elevations (Brooks et al., 2012). Similarly, in the headwater catchments of the Colorado River, high-elevation snowmelt contributes disproportionately (up to 70%) to streamflow during peak snowmelt periods, with greater high-elevation snowmelt contributions in years with lower snowpack and warmer spring temperatures (Sprenger et al., 2024). Numerous studies (Van Tiel et al., 2024) in cold regions have shown that seasonal snowmelt and glacial melt often account for the majority of streamflow during the melt season, such as in the European Alps (Engel et al., 2015; Penna et al., 2014; Schmieder et al., 2019), the Andes (Gribbin et al., 2024; Ohlanders et al., 2013), Svalbard (Blaen et al., 2014), the Wind River Range in Wyoming (Cable et al., 2011), the Tibetan plateau (Zongxing et al., 2015), and the Himalayas (Maurya et al., 2010; A. Lone et al., 2021; Dar et al., 2024). However, snow is not always over-represented in streams relative to its proportion in annual precipitation, as evidenced in the Swiss Alps (Allen, von Freyberg, et al., 2019).

As a complement to end-member mixing, an "end-member splitting" approach has been proposed to move beyond only identifying the sources of streamflow, to exploring where precipitation ultimately goes. Kirchner and Allen (2020) illustrated this approach using isotope time series to infer the fates of summer and winter precipitation at Hubbard Brook, New Hampshire, USA (Figure 5). Their results show that end-member splitting can lead to different insights than end-member mixing. For example, at Hubbard Brook, about one-sixth of

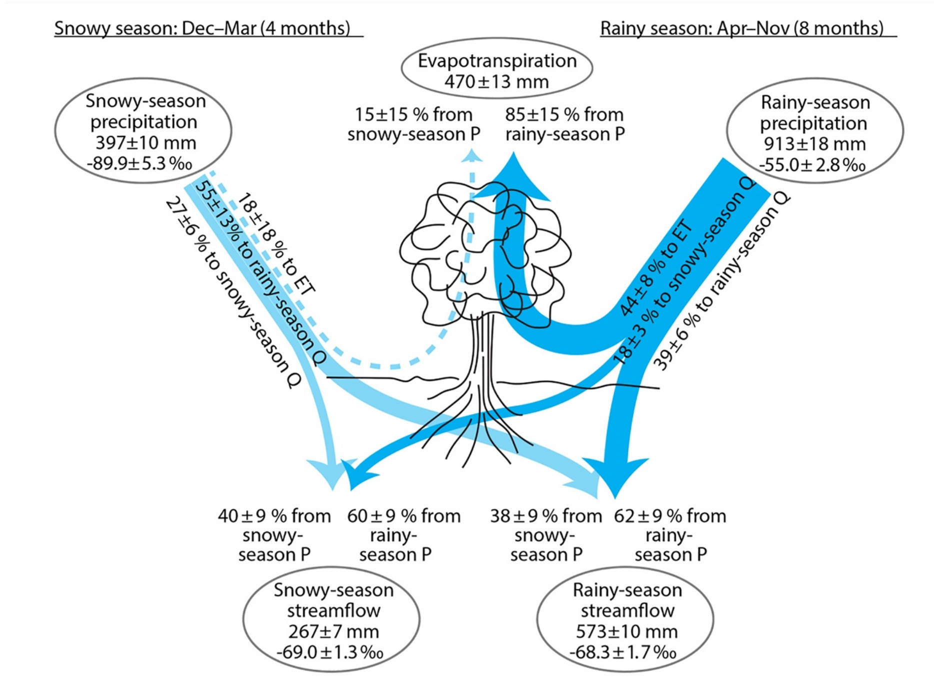

Figure 5. End-member splitting results illustrating how precipitation (P) is partitioned into streamflow (Q) and evapotranspiration (ET) during the snow-dominated season and the rain-dominated season at Hubbard Brook, US (analysis by Kirchner and Allen (2020) based on 4 years of fortnightly ^{2}H measurements by Campbell and Green (2019)). Wider lines indicate larger water fluxes; dashed lines show fluxes that differ from zero by less than one standard error.

rainy-season precipitation is discharged during the snowy season (end-member splitting), but this accounts for over half of snowy-season streamflow (end-member mixing). Conversely, roughly half of snowy-season precipitation is discharged during the rainy season, accounting for nearly 40% of rainy-season streamflow. Each season's precipitation contributes significantly to the following season's streamflow, implying substantial inter-seasonal storage in snowpacks and groundwaters. Marttila et al. (2021) used end-member splitting to show that rainfall at the Lompolonjängänoja catchment in Finland is partitioned roughly equally between streamflow and evapotranspiration, but snowfall predominantly leaves the catchment via evapotranspiration. Sprenger et al. (2022) applied the end-member splitting approach to nine headwater catchments in the Rocky Mountains and found that in catchments with higher tree cover, more snow becomes evapotranspiration, leaving less snowmelt available to sustain summer flows. These examples illustrate the contrasting insights that emerge from asking not only where streamflow or evapotranspiration comes from, but also where precipitation goes.

4.2.2. Lake Water

4.2.2.1. Lake Water and Its End-Members in Time and Space

End-member sources of lake waters include direct precipitation, groundwater, stream/river water, and soil water (Figure 4). Groundwater contributions are particularly important in karstic areas and humid regions (Hayashi et al., 2016; Valiente et al., 2020), but quantifying groundwater inflows into lakes remains challenging due to the heterogeneous spatiotemporal distributions of groundwater flow (Isokangas et al., 2015; Rosenberry et al., 2015) (Section 4.5). The temporal delineation of end-members ranges from single precipitation events to seasonal (e.g., spring snowmelt) and even multi-year periods (Shaw et al., 2014).

4.2.2.2. Sampling Lake Water and Its End-Members in Time and Space

Estimates of long-term water balances in lakes typically assume isotopic steady state and complete mixing of lake water (J. Gibson et al., 2016). However, verifying this assumption requires water sampling both horizontally across the lake and vertically along the water column (Rozanski et al., 2001). Vertical profiling of stratified lakes is essential to accurately quantify end-members (Ross et al., 2015), and to document variations in tracer composition with depth, given the influence of seasonal temperature fluctuations on water quality, oxygen levels, and nutrient dynamics (Deeds et al., 2021; Perga et al., 2023; S. Wang et al., 2022). Horizontal sampling across the lake is equally important to capture lateral heterogeneity driven by factors such as wind direction, stream inflows, and groundwater discharge patterns (Lewandowski et al., 2015). To quantify temporal variability, sampling at regular intervals, ranging from sub-daily to yearly periods, is often necessary (e.g., Valiente et al., 2018).

4.2.2.3. Lake Water: Mixing Model Applications

Mixing models have been used to quantify components of the water balance that are challenging to measure directly, such as groundwater inflows (Pierchala et al., 2022), lake evaporation (Dinçer, 1968; J. J. Gibson et al., 1996; Welch et al., 2017; Brooks et al., 2014), and catchment-scale evaporation-transpiration partitioning (J. J. Gibson & Edwards, 2002; Jasechko et al., 2013). Tracer characterization in lakes provides insights into processes such as river intrusion (Cotte & Vennemann, 2020), transient flood contributions to the lake water balance (Masse-Dufresne et al., 2021) and biogeochemical cycling in lakes and reservoirs (Dong et al., 2022; Valiente et al., 2022).

Lake evaporation and its isotopic composition are key components in mixing model analysis, particularly in (semi-)arid regions (Sanz et al., 2022), yet their direct measurement remains difficult. Stable isotopes of lake water are the primary tracers used in lake water balance studies since evaporation preferentially enriches the heavier isotopes in the lake water that is left behind (Brooks et al., 2014; Voigt et al., 2021). Incorporating additional tracers, such as ^{17}O in a "triple mass balance" approach, have been shown to complement traditional ^{2}H and ^{18}O analyses of lake evaporation (Pierchala et al., 2022). The isotopic composition of evaporating water is commonly estimated from temperature, humidity, and the isotopic composition of the surface water and ambient air using the Craig-Gordon model (Craig & Gordon, 1965). However, the isotopic composition of local atmospheric water vapor, a crucial input in the model, is rarely measured directly, and inferring it from precipitation can be problematic (J. Gibson et al., 2016). Crawford et al. (2019) showed that precipitation-equilibrium isotope ratios were poor predictors of the isotopic composition of atmospheric water vapor between precipitation events, and proposed an evaporation pan method as an alternative.

Recent advances in in situ measurement technologies have led to direct measurements of isotopes in water vapor around lakes (Chazette et al., 2021). These instruments support the development of both discrete and continuous monitoring systems, which are essential to capture short-term variations driven by weather events (e.g., rainfall, windstorms), and longer-term trends influenced by seasonal changes or anthropogenic activities. Such advances have the potential to considerably improve our understanding of the hydrological functioning of lentic ecosystems.

4.3. Soil Water

4.3.1. Soil Water and Its End-Members in Time and Space

Soil water is sourced from end-members such as precipitation, snowmelt, or groundwater. In turn, soil water is a potential source for plant water uptake, streamflow and groundwater (Figure 6).

Geochemical tracer concentrations in soil water can change over time, not only via interactions with other end-members, but also through biogeochemical reactions and evapoconcentration. Evaporation also enriches stable isotopes of soil water, with the result that the relationship between δ^2H and δ^{18}O in soil waters often deviates from the local meteoric water line (LMWL) that characterizes local precipitation. Soil water δ^2H and δ^{18}O values usually plot along a trendline that is less steep than the LMWL (see green dashed line in Figure 7), representing precipitation that has evaporated by different amounts in different seasons. Individual δ^2H and δ^{18}O values in soil waters can be projected back onto the LMWL using evaporation lines inferred from ambient temperature and humidity data (Benettin et al., 2018; Bowen et al., 2018), thus estimating the isotopic signature of the soil's precipitation source water and facilitating mixing analyses (Figure 7).

In soil water, isotope fractionation signals from evaporation usually decrease with soil depth due to mixing with precipitation that has infiltrated rapidly, with little evaporative fractionation (Sprenger et al., 2016). Analogous to the event-based hydrograph separation later described in Section 4.2, contributions of recent precipitation to soil

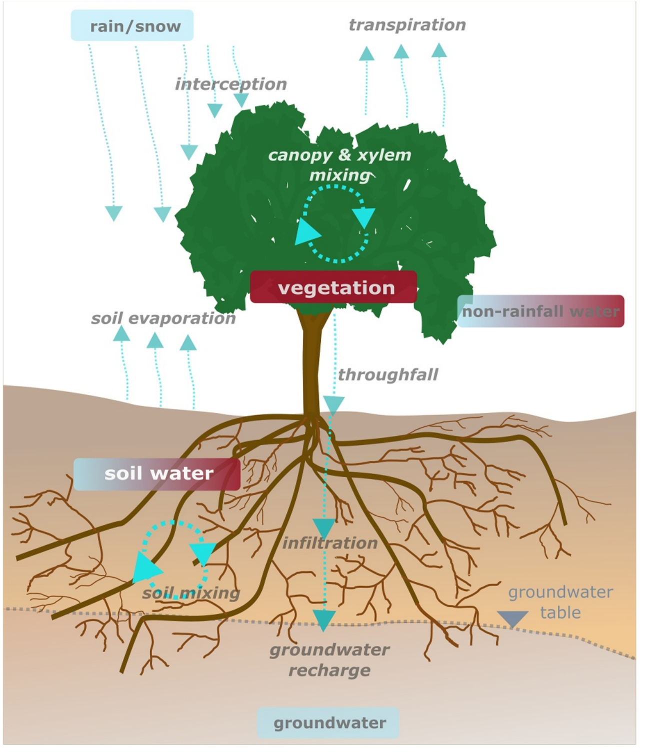

Figure 6. Water exchange and mixing in the atmosphere-vegetation-soil continuum. Blue boxes represent end-members, red boxes represent mixtures, and the blue-red box represents both end-members and mixtures.

water can be estimated by two-component end-member mixing (Equation 1), using the pre-event soil water and the precipitation input as end-members, and the post-event soil water as the mixture.

Instead of sampling the soil water itself, one can also infer soil water composition by sampling plant xylem water, assuming that it represents an integrated sample across the plant's rooting zone (Luo et al., 2019). However, where root water uptake is not equally distributed across the rooting zone, the results will be biased toward depths of higher root density and water availability (Kulmatiski et al., 2017).

4.3.2. Sampling Soil Water and Its End-Members in Time and Space

The optimal sampling frequency of soil water will depend on the research question and the site conditions. For example, monthly sampling intervals are sufficient for mixing models to determine how winter and summer precipitation contribute to soil water storage (e.g., Sprenger, Llorens, et al., 2019). By contrast, daily or weekly sampling would be required to study snowmelt infiltration and mixing with previously stored soil water (e.g., Hürkamp et al., 2018; Muhic et al., 2023).

Spatial sampling strategies must take account of both the vertical and horizontal variability in soil water tracers. For example, investigations of groundwater recharge might focus on sampling deeper soil layers (Koeniger et al., 2016), whereas understanding rainfall infiltration and its mixing with pre-event water would require also sampling the shallow soil layers (e.g., Sprenger et al., 2017). Seepage outflows at trenches or from weighing lysimeters provide integrated signals from the contributing flow paths, and thus cannot identify depth-specific mixing across the soil profile (Imig et al., 2023). However, soil water sampling across the soil profile can reveal the mixing processes behind the tracer signals observed at the outlet of lysimeters or trenches (Benettin, Nehemy, Asadollahi, et al., 2021).

Volumetric soil water content and the corresponding tracer concentrations also exhibit very high lateral heterogeneity, which is difficult to capture with practically feasible sampling schemes (Beyer & Penna, 2021). Initial screening of this variability with a manageable number of samples can potentially facilitate estimates of the number of parallel samples (i.e., samples taken at the same time from different locations) that would be needed to

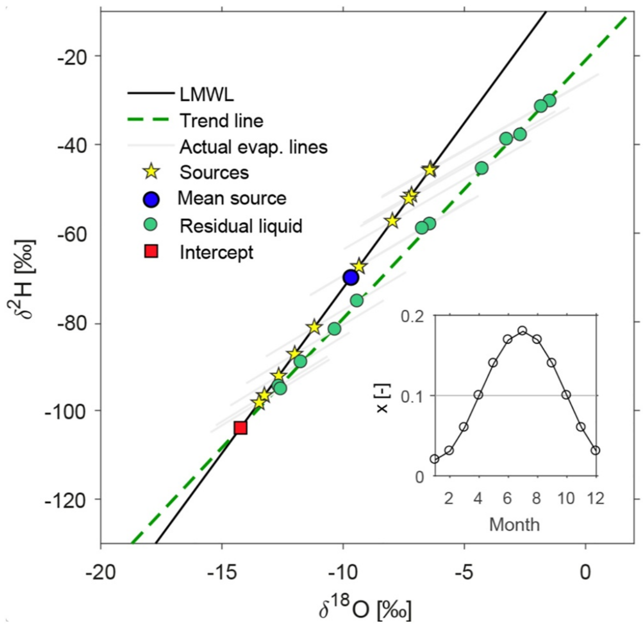

Figure 7. Example from Benettin et al. (2018) showing the kinetic effect of evaporation on residual water isotopes from seasonally varying precipitation using a synthetic data set. The evaporatively fractionated residual water samples (green dots) cluster around a trend line (dashed green line), with considerably steeper slopes than the individual evaporation lines (gray lines). Inset depicts the assumed annual cycle in evaporated fractions x.

achieve the desired precision in the average tracer signature. However, the relevance of such an average will often be unclear because water flow in soils is often strongly preferential (i.e., a large fraction of the flow passes through a small fraction of the volume).

When soil water is used as an end-member, knowledge about its spatial and temporal variability is crucial for interpreting its contributions relative to other end-members like precipitation or groundwater. For example, Correa et al. (2017) showed that Andosols and Histosols in their study catchment had significantly different soil water ion concentrations, and based on these differences, they showed that during the dry season, soil water from Andosols was contributing less to the catchment runoff than Histosols.

4.3.3. Soil Water: Mixing Model Applications

Mixing models have been applied to the unsaturated zone much less often than to streamflow, owing to the difficulties in obtaining soil water tracer data. Nevertheless, mixing analyses using soil water tracers have revealed important insights into water mixing along heterogeneous preferential flow paths (Radolinski et al., 2021). A mixing model study of soil water in a Mediterranean climate (Spain) showed that the contribution of event water to soil pores in monthly sampling intervals was strongly correlated with the soil moisture content prior to the events because precipitation was more likely to refill empty pore spaces in drier soils (Sprenger, Llorens, et al., 2019). The rewetting of the soil water storage driven by newly infiltrating water was further investigated in a Mediterranean region in South Australia, revealing that the portion of newly infiltrated water was highest in the first storms following the end of the dry season (Xu et al., 2019).

Event water will infiltrate the fastest and deepest when preferential flow paths exist. Recent laboratory experiments used isotope-based mixing analyses to assess the impact of preferential flow paths on event water infiltration and mixing (Radolinski et al., 2021; Williams et al., 2023). In addition, field experiments using isotopically-labeled water coupled with mixing models could be applied to map the infiltration of stemflow and its contribution to soil water at different depths and distances from individual trees (Zuecco et al., 2025). With sufficiently dense sampling, it is possible to estimate the stemflow infiltration area (Pinos et al., 2023; Van Stan & Allen, 2020; Zuecco et al., 2025). In situ measurements of stable isotopes of water on the plot scale also open up new opportunities for short-term mixing investigations. For example, Volkmann et al. (2016) measured ^{2}H breakthrough at soil depths of 5–60 cm in response to a pulse of ^{2}H-labeled precipitation, applying a Bayesian mixing model (Erhardt & Bedrick, 2012) to quantify how infiltration lag times varied with soil depth.

End-member mixing studies at agricultural sites in temperate regions have shown that subsurface stormflow sampled at tile drains consists of about 20%–30% event water (Granger et al., 2010; Zajíček et al., 2016), consistent with the mobilization of previously stored water to comprise the remaining 70%–80% of soil water drainage (Smith et al., 2021).

Soil water contributions to streamflow are highly relevant as a source of nutrients and contaminants. An end-member mixing study of a small Arizona catchment estimated that soil water contributions varied seasonally from 21% to 62% of streamflow (Dwivedi et al., 2019). Soil water also represents a critical link controlling surface-atmosphere exchange by acting as a reservoir for potential evapotranspiration loss, and an important regulator of runoff generation processes.

4.4. Plant Water

4.4.1. Plant Water and Its End-Members in Time and Space

Plants function as conduits between the atmosphere and the soil: plants absorb water from the soil through their roots, transport it to the leaves via the xylem, and release it into the atmosphere through the stomata. Plants also

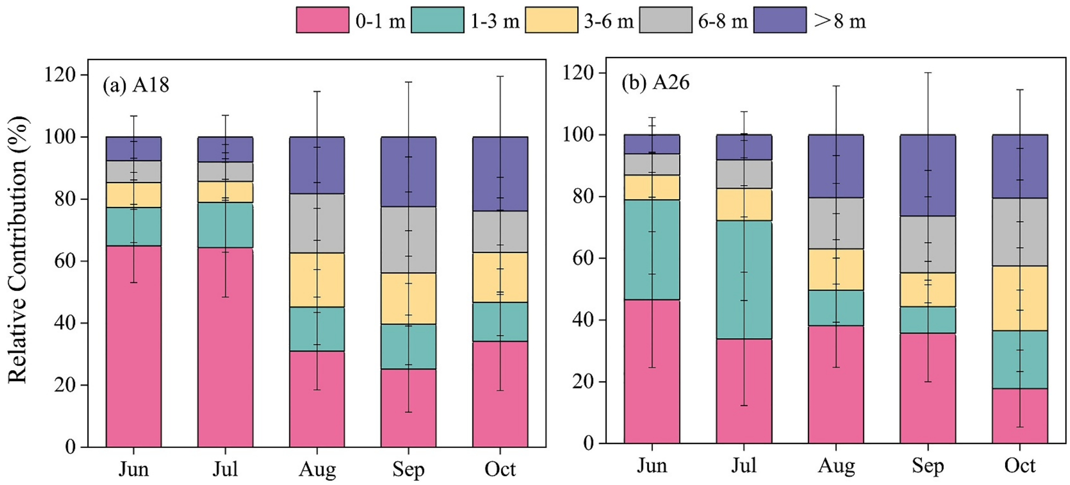

Figure 8. The relative contributions of water from different soil layers to xylem water of apple trees of different ages (a=18 years and b=26 years), using stable water isotopes and a Bayesian mixing model (MixSIAR). Figure and data from Gai et al. (2023).

function as atmosphere-soil interfaces in the opposite direction, intercepting precipitation and modifying its tracer composition before it infiltrates the soil (Allen et al., 2013; Xia et al., 2023) (Figure 6).

Plants primarily source water from different soil depths and groundwater via their root systems. Taking representative samples of these potential sources is challenging, because plant root distributions are often unknown. Plants also absorb water through their leaves, a process known as foliar water uptake (e.g., Berry et al., 2018). Estimating the extent of foliar water uptake is difficult because it involves sampling leaf water, which undergoes significant changes in its tracer composition due to evaporation through stomatal openings.

End-member mixing models are used to estimate the different sources of plant water uptake (Figure 8), mostly using stable water isotopes (e.g., Gai et al., 2023; Rothfuss & Javaux, 2017; Sutanto et al., 2012). However, waters in the different compartments, including leaves and near-surface soils, can be significantly evaporated or mixed with atmospheric water vapor (Section 4.1; Benettin et al., 2018; Bowen et al., 2018; Holloway-Phillips et al., 2016; Jiménez-Rodríguez et al., 2020; Li et al., 2021). These effects need to be corrected before conducting the mixing analysis. Tracer measurements in other end-members such as precipitation and groundwater are relatively straightforward, however their spatial and temporal variability should be taken into account (Sections 4.1 and 4.5).

4.4.2. Sampling Plant Water in Time and Space

In tracer-aided mixing modeling studies, plant water is typically sampled from the xylem, most often by extracting water from mature stems or branches. Sampling is usually conducted less frequently than for soil or surface waters due to the labor-intensive nature of collection and analysis, but is strategically timed to capture key hydrological or phenological transitions. Sampling commonly focuses on different stages of the growing season, periods before and after rainfall events, or periods of water stress such as droughts. Sampling locations are generally co-located with soil and groundwater sampling sites to allow direct comparisons with potential water sources. Studies often target dominant or functionally diverse plant species to capture variability in water uptake strategies (Ceperley et al., 2024).

4.4.3. Plant Water: Mixing Model Applications

Isotopic mixing models have been crucial in elucidating water mixing dynamics across the soil-plant-atmosphere interface (Orlowski et al., 2023). An important focus of mixing models in plant water uptake studies is to partition evapotranspiration into soil and canopy evaporation and plant transpiration (Dubbert et al., 2013; Good, Soderberg, et al., 2014; L. Wang et al., 2010). This is particularly relevant in agricultural applications, where minimizing evaporative losses is crucial for ensuring adequate plant water availability during times of water scarcity. Numerous studies have used stable water isotopes to show that different irrigation schemes, tillage methods, and crop rotation practices influence evapotranspiration partitioning (e.g., Liebhard, Klik, Stumpp, Morales Santos, et al., 2022; Liebhard, Klik, Stumpp, & Nolz, 2022).

Isotope-based mixing models are often used to quantify where plants take their water from, which improves our understanding of their rooting systems, water flow in the unsaturated subsurface, and plants' adaptation strategies to different environmental conditions (Carrière et al., 2020; Gessler et al., 2021). For example, Allen, Kirchner, et al. (2019) showed that alpine trees predominantly rely on winter precipitation, challenging the common assumption that their primary water source is growing-season precipitation. The dominant role of winter precipitation in tree water uptake has been shown in regions with dry growing seasons (Brooks et al., 2010) as well as in regions with year-round precipitation (Floriancic et al., 2024; Goldsmith et al., 2022). However, studies in the tropical cloud forest in Peru have also shown that plant-water uptake can be in sync with the seasons, with plants accessing wet-season precipitation during the wet season and dry-season precipitation during the dry season (Burt et al., 2023). Floriancic et al. (2024) showed that plant water uptake is constrained by available soil moisture within the rooting zone, a factor that varies among tree species and seasons. During periods of ample soil water availability, plant water uptake is maintained at normal levels, but it declines during soil drying, as observed in beech trees during the 2018 drought in Switzerland, where increased relative uptake from deeper soil depth could not compensate for the lack of available water at shallow soil depths (Gessler et al., 2021). In the Northern Rockies, Douglas fir trees in lower-elevation, water-limited environments rely on winter precipitation sourced from deeper soils, whereas Douglas fir trees in higher-elevation, water-excess environments primarily use summer precipitation from near-surface soil layers (Martin et al., 2018). Mixing analyses using tree ring cellulose ^{18}O in the Rocky Mountains indicate that conifer trees primarily use snowmelt water, but may also use summer rainfall during high-growth years in response to higher precipitation during periods of maximum plant water demand (Berkelhammer et al., 2020).

While many studies have focused on plant water uptake from different soil depths, few have investigated the use of stemflow by trees. One exception is Snyder et al. (2024)'s use of labeling experiments to detect a small but significant fraction of stemflow used by piñon and juniper trees, which was not associated with detectable changes in sap flow rates or plant water potentials. Further studies are needed to investigate the role of stemflow in plant water uptake, particularly compared to throughfall, and under different soil wetness conditions and precipitation intensities.

4.5. Groundwater

4.5.1. Groundwater and Its End-Members in Time and Space

Groundwater can be sourced from all compartments of the water cycle (e.g., Jasechko, 2019) (Figure 4): rainfall, snowmelt (e.g., R. W. Carroll et al., 2019; Penna et al., 2014; Schilling et al., 2021), glacial melt (Miller et al., 2021), infiltration from lakes and streams (e.g., Engel et al., 2022; Isiorho & Matisof, 1990; Popp, Pardo-Alvarez, et al., 2021), inter-aquifer flow (e.g., Popp et al., 2019; Thiros et al., 2023) and permafrost thaw (e.g., Lamontagne-Hallé et al., 2018). In turn, groundwater can also be a source for plant water uptake (e.g., Bertrand et al., 2012; Knighton et al., 2021), soil moisture (e.g., Martínez-de la Torre & Miguez-Macho, 2019) and surface waters (e.g., streams, rivers, lakes and wetlands) (e.g., Winter et al., 1998) (Figure 4).

The tracer composition of groundwater is variable in space and time, reflecting subsurface heterogeneity (e.g., Kiewiet et al., 2019) and seasonally varying contributions from different end-members (e.g., rain or snow) (Jasechko, 2019). However, it is not well understood how the variability in the end-members contributes to variability in groundwater composition. While most tracer studies map out the different sources recharging groundwater, few have considered the time lag between tracers entering the CZ and their appearance in groundwater (Beria et al., 2020; Popp, Pardo-Alvarez, et al., 2021). This consideration is crucial as these delays can vary with the hydrological state of the catchment (see Figure 9). For instance, precipitation can be expected to recharge underlying aquifers faster when it falls on wet landscapes than on dry ones. This is particularly relevant in snowy regions, where snowmelt has a disproportionately high impact on groundwater recharge since the catchment is wet during the snowmelt period (Beria et al., 2018).

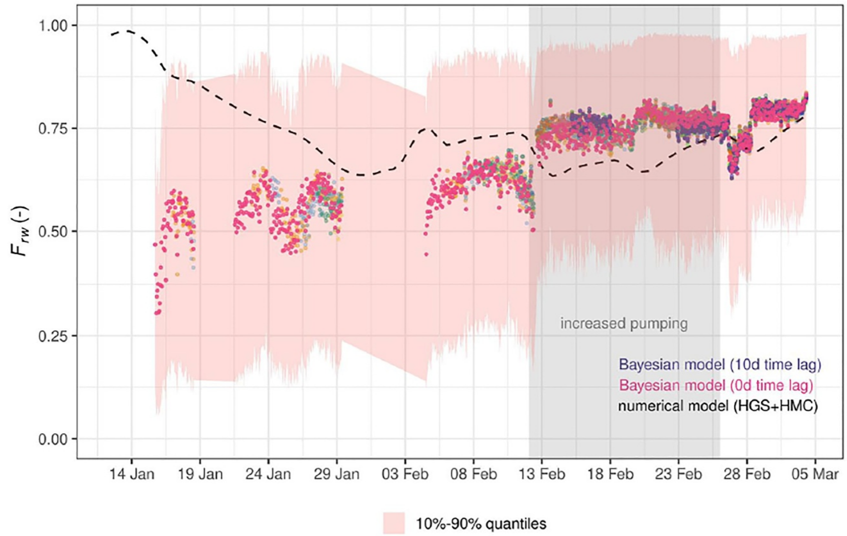

Figure 9. Estimated fraction of river water (F_{rw}) in groundwater derived from a Bayesian mixing model where one end-member is river water and the other is regional groundwater. Colors indicate different time lags between 0 and 10 days that the river water potentially took to travel from the river to the groundwater well where the mixture was analysed (for simplicity, the legend only shows 0 and 10 days; the black dashed line shows results from a physically-based model; HydroGeoSphere). Figure from Popp, Pardo-Alvarez, et al. (2021).

4.5.2. Sampling Groundwater in Time and Space

Groundwater is sampled either through groundwater wells, or through springs which discharge water from underlying aquifers. As springs are not widely available, most groundwater measurements involve sampling existing wells or installing new ones, which typically entails high costs for drilling. Consequently, groundwater studies are often more data-limited than surface water studies. The financial, logistic, and technical challenges of sampling groundwater are even more pronounced in mountainous and arctic environments. As a result, groundwater systems in these regions are under-studied, even though they have been experiencing rapid changes due to global warming (Van Tiel et al., 2024).

Keeping in mind these limitations, it is helpful to have a preliminary conceptual model that provides insights into potential end-members and their variability before starting a detailed field campaign (Enemark et al., 2019). A preliminary field study using easily measurable tracers, such as water temperature, electrical conductivity (EC), and pH, which can readily be assessed with a handheld field probe, can provide a broad overview of groundwater composition and help define an initial conceptual model. Such preliminary studies, in combination with available hydrometric measurements (e.g., water table data), can help to define a sampling scheme that fits the research question and the resources at hand. When designing a sampling scheme, it is important to account for groundwater depth: shallow groundwater shows significant spatial and temporal variability in tracer signals, while deeper groundwater, often isolated from surface waters, typically has less tracer variability (e.g., Jasechko, 2019). Finally, sampling should capture the variability of hydrological conditions over time. Depending on the research question and site-specific dynamics, it may be necessary to sample across different hydrologic regimes to gain deeper insights. The sampling frequency should be tailored to the objectives of the study and the response characteristics of the aquifer.

4.5.3. Groundwater: Mixing Model Applications

Globally, groundwater systems are changing rapidly due to excessive groundwater pumping, land-use changes and warming-induced alterations in precipitation patterns (e.g., Famiglietti, 2014; Jasechko et al., 2024). Moreover, in cold regions increased glacial melt, earlier snowmelt and increasing prevalence of ephemeral snowpacks are altering the timing and magnitude of groundwater recharge (Van Tiel et al., 2024). Several mixing model studies have shown that in snow-impacted regions, snowmelt has a larger impact than summer rainfall on groundwater recharge (Beria et al., 2018). This has been observed in diverse geographic settings, ranging from

California's Sierra Nevada (Winograd et al., 1998) to the European Alps (Penna et al., 2014, 2017), the Andes (Herrera et al., 2016) and the Himalayas (Jeelani et al., 2017; S. A. Lone et al., 2021). A few studies in mountainous landscapes have also estimated the average altitude at which snowmelt recharges aquifers using the isotopic lapse rate (i.e., the change in average isotopic composition of precipitation with elevation) (Arellano et al., 2020; Kohfahl et al., 2008). More recently, recharge temperatures inferred from noble gases have been used to assess the impact of snowmelt dynamics on groundwater recharge (Schilling et al., 2021). Schilling et al. (2021) found that mixing models using dissolved gases provide better-constrained estimates of groundwater recharge from snowmelt than mixing models based on stable isotopes of water. In glacierized landscapes, glacial meltwater streams and subglacial flows are both derived from glacier melt water, and thus cannot be readily distinguished based on their stable isotope signatures. However they can be distinguished based on electrical conductivity, because subglacial flow has higher ion concentrations and thus higher EC (Zuecco et al., 2019). These examples illustrate how using multiple (and novel) tracers can lead to more robust assessments of dominant hydrological processes, especially if relevant water sources are not clearly identifiable using one tracer alone.

Tracers have also been used to quantify the relative contribution of older groundwater that is stored within deeper aquifers, at timescales of 1000s of years. Tracers such as ^{14}C, ^{4}He, and $^{234}U/^{238}U$ are typically used to assess mixing with very old groundwater (Table 1). Azevedo da Silva et al. (2020), for instance, document a case in which a geologically older (and deeper) aquifer has a shorter mean groundwater residence time than the geologically younger (and shallower, but less permeable) aquifer that overlies it. Santoni et al. (2021) used a combination of tracers to show that a Mediterranean peatland was dependent on deep groundwater in spring and summer, and on surface water and shallow groundwater in fall and winter. Similarly, Petersen et al. (2018) used a combination of tracers to show that the Algerian Atlas Mountains are the primary contributor to groundwater recharge of the Continental Intercalaire aquifer—a continental-scale aquifer of major importance in North-Western Africa. Mixing models using stable isotopes and geochemical tracers have also shown that groundwater originating from Pleistocene ice sheets is preserved in several North American and European aquifers, and is used for public water supply (Clark et al., 2000; Pärn et al., 2016). Mixing models have also been used to identify how different aquifers are connected to surface water bodies. For example, Popp et al. (2019) detected the contribution of an old groundwater component to regional and very young groundwater by using high-resolution in situ analyses of ^{4}He and other tracers, in combination with a Bayesian end-member mixing model. In Cambodia's Kandal Province, mixing models using stable water isotopes were used to estimate the relative extent of evaporation of the different groundwater recharge sources in arsenic-affected aquifer (Richards et al., 2018). Groundwater recharge from surface waters has also been quantified using mixing models in Southeastern France, where Poulain et al. (2021) quantified groundwater recharge from three different river water end-members that differ in residence times. Their study showed that end-member contributions differ at pumping wells even though they are very closely located to each other (within 70 m) and have similar depths. Comparing isotopic tracers and geochemistry allowed the authors to quantify the groundwater contributions from different hydrological compartments. In a pre-alpine Swiss valley, Popp, Pardo-Alvarez, et al. (2021) used quasi-continuously analyzed ^{4}He concentrations to estimate the fraction of groundwater recharged by recently infiltrated river water. Only high-resolution time-series data allowed the authors to properly assess the system response to forcing such as increased river discharge. Moreover, they showed that the common assumption of constant end-members can be inaccurate. They found that, on average, the majority (∼70%) of the groundwater mixture originated from recently infiltrated river water. In a site near the Colorado River Christensen et al. (2018) found using strontium isotopes that vadose zone pore water contributed up to 38% of aquifer recharge, with the exact contribution depending on the site's microtopography. In summary, these studies underscore the critical role of mixing models in advancing our understanding of groundwater recharge and discharge dynamics.

5. Outlook

This outlook highlights research directions that have the potential to advance the understanding of Critical Zone processes by enhancing or complementing more traditional tracer-aided mixing modeling approaches covered so far in this review.

5.1. Advances in Tracer Measurement and Data Collection Techniques

Advances in measurement technologies are making tracer measurements more affordable and accessible, thereby enhancing their spatial coverage, while emerging in situ measurement capabilities are enhancing their temporal resolution. Both developments are expanding the availability of tracer data for hydrological analyses (e.g., Popp, Manning, & Knapp, 2021). There is much to be learned by expanding tracer data collection in regions with coarse spatial coverage (e.g., the Arctic, Africa, South America, etc.), synthesizing published data, and collating existing data sets from regional and national networks (Massoud et al., 2023).

Recent developments in novel tracers, such as fluorescence proxies for particulate organic matter (Derrien et al., 2020), noble gas temperatures for groundwater dynamics in snow-dominated landscapes (Schilling et al., 2021), and in situ potable mass spectrometers measuring noble gas tracers (Popp, Manning, & Knapp, 2021) can offer additional insights into water flow pathways. Recent studies highlight the value of incorporating ^{17}O-excess into hydrological analyses alongside δ^2H and δ^{18}O. Because ^{17}O-excess is relatively insensitive to temperature but sensitive to humidity (Angert et al., 2004), it offers a unique constraint on kinetic processes such as evaporation. For example, ^{17}O-excess has been used to detect non-steady-state evaporation during dew formation (Tian et al., 2021), improve lake evaporation estimates (Pierchala et al., 2022), and differentiate drought mechanisms in Southern Africa (Kaseke et al., 2018). These findings underscore the potential of ^{17}O-based tracers to advance our understanding of evaporation and moisture source dynamics. However, some of these tracers remain costly and labor-intensive, limiting their widespread usage. As long as certain tracers can only be analyzed by a few specialized laboratories, their applications will be limited.

Citizen science—also termed community science—initiatives present an opportunity to considerably expand the scope and scale of tracer data collection for water research. Citizen/community science projects have generated extensive data on stream water quality and the isotopic composition of rainfall events, groundwater, surface water, and tap water (Bowen et al., 2007; Cole & Boutt, 2021; de Wet et al., 2020; Good, Mallia, et al., 2014; Njue et al., 2019; Ramírez et al., 2023). By collecting water samples, reporting local hydrologic conditions, and participating in data analyses, citizen/community scientists can help generate higher-resolution data sets. This approach not only enhances hydrological research, but also promotes public engagement, trust in scientific findings, and awareness of water-related issues.

5.2. New Data Sources and Interdisciplinary Research

The use of satellite-based remote sensing data has increasingly gained traction in hydrological research in recent years (Beria et al., 2017; Dembélé et al., 2020; Jiang & Wang, 2019). These data sets provide broad spatial coverage of numerous hydrometeorological variables (e.g., precipitation, temperature, snow coverage, etc.), which when combined with tracers, can help map water flow pathways and elucidate hydrological processes at larger spatial scales, which are otherwise inaccessible to tracer-based studies (He et al., 2021). Remote sensing data sets can also validate and refine the outputs of mixing models. One such application was in the western Himalayas, where S. A. Lone et al. (2017) used LiDAR data in conjunction with glacial meltwater isotopes to reveal divergent glacial melt patterns at different altitudes through the year. Similarly, Sprenger et al. (2024) combined streamflow d-excess values with snowmelt estimates using Airborne Snow Observatory (ASO) flights to quantify the contributions of high- and low-elevation snowmelt to streamflow in three Colorado river basins. New satellite data sets enable the monitoring of water vapor isotopes globally at a daily resolution (Schneider et al., 2022). These data sets are becoming important inputs for large-scale hydrological models that incorporate isotope data, although their applications at the catchment scale are still emerging.

Beyond the integration of tracer and satellite data, the inclusion of other data types, such as groundwater levels, meteorological data, and ecological indicators (e.g., vegetation cover, microbial communities, and biodiversity indicators), can enhance our understanding of water flow dynamics within the Critical Zone. For instance, changes in vegetation cover can directly influence evaporation rates, thereby impacting the overall catchment water balance. Similarly, land use changes resulting from forest fires can dramatically alter streamflow dynamics.

5.3. Machine Learning Techniques

The advent of machine learning (ML) has revolutionized data analysis across various disciplines by uncovering patterns and relationships within large complex data sets. In hydrology, ML holds significant promise for enhancing our understanding of non-linear water flow dynamics within the Critical Zone. To date, the applications of ML in tracer hydrology have primarily been limited to predicting isotopic ratios in hydrological fluxes. For example, Sahraei et al. (2021) used a Long Short-Term Memory (LSTM) model to predict streamflow and groundwater isotopes at a 3-hr resolution, indicating the potential for gap-filling high-frequency streamflow isotope records. ML has also been employed to estimate precipitation isoscapes across Europe (Nelson et al., 2021), thereby extending the applicability of mixing models to regions where direct sampling of precipitation isotopes may not be feasible.

ML models are emerging as an alternative that can out-perform traditional water quality models, given sufficient training data (Zhi et al., 2024). However, the "enormous" data sets needed to train ML models (Zhi et al., 2024) are usually unavailable in tracer hydrology. A further challenge is that ML models often perform poorly when predicting beyond the range of their training data—precisely where models are most urgently needed to supplement observations. Physics-informed ML has potential to integrate prior physical knowledge into neural networks, thereby constraining the parameter space (Shen et al., 2023). However, ML applications in tracer-aided hydrological modeling remain largely unexplored.

5.4. Tracers in Earth System Models (ESMs) and Other Large-Scale Modeling Approaches

ESMs are essential tools for addressing modern environmental challenges, including the UN's six transformation goals, which highlight linkages between the Sustainable Development Goals (SDGs) (Sachs et al., 2019). However, inadequate knowledge, data, and models constrain our understanding of cause-effect dependencies that are crucial for informing global climate adaptation practices. Although ESMs can theoretically predict complex environmental and human interactions, their computational demands limit coupled simulations of Earth's systems. Resolving the multitude of CZ processes requires many model parameters, and determining realistic parameter values is crucial to improve the reliability of ESMs for their subsequent use in climate change impact assessments (Holmes et al., 2023). However, many regions lack sufficient hydrological data for robust parameter estimation of ESMs, restricting their use and accuracy (Stadnyk & Holmes, 2023).

Tracer-aided ESM modeling, integrating tracer observations with hydrometric data, can improve parameter identifiability and the representation of CZ processes in large-scale models (Holmes et al., 2023; Jung et al., 2025; Stadnyk & Holmes, 2020, 2023). Currently, only a few ESMs simulate tracers directly (IAEA, 2023), highlighting opportunities to expand their capabilities. Tracer integration can be performed either offline by using mixing modeling results to constrain specific ESM parameters, or by implementing particle tracer routines within ESMs and then using tracer data directly during ESM calibration (similar to the approaches that have been used to integrate particle-tracking in hydrological models, e.g., Dennedy-Frank et al. (2024); Kuppel et al. (2018)). Tracer modules that can directly plug into existing ESMs hold promise for rapid progress in tracer-aided ESM modeling.

Advancing tracer-aided modeling requires a concerted effort to establish common practices with shared standards and model evaluation benchmarks (IAEA, 2023). Despite numerous tracer-aided modeling studies, inconsistencies remain in the metrics used for model evaluation and in the standards for what constitutes "acceptable" performance (Holmes et al., 2023). Open sharing of data, code, and workflows within the community (Hall et al., 2022; Knoben et al., 2022) is essential for advancing Critical Zone research.

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Conflict of Interest

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

Data Availability Statement

Data were not used, nor created for this research. The Supporting Information for Table 1 can be accessed via Popp et al. (2025).

References

Abbott, B. W., Baranov, V., Mendoza-Lera, C., Nikolakopoulou, M., Harjung, A., Kolbe, T., et al. (2016). Using multi-tracer inference to move beyond single-catchment ecohydrology. *Earth-Science Reviews*, *160*, 19–42. https://doi.org/10.1016/j.earscirev.2016.06.014

Agam, N., & Berliner, P. (2006). Dew formation and water vapor adsorption in semi-arid environments—A review. *Journal of Arid Environments*, *65*(4), 572–590. https://doi.org/10.1016/j.jaridenv.2005.09.004

Aguirre-Gutiérrez, C. A., Holwerda, F., Goldsmith, G. R., Delgado, J., Yepez, E., Carbajal, N., et al. (2019). The importance of dew in the water balance of a continental semiarid grassland. *Journal of Arid Environments*, *168*, 26–35. https://doi.org/10.1016/j.jaridenv.2019.05.003

Ala-aho, P., Tetzlaff, D., McNamara, J. P., Laudon, H., Kormos, P., & Soulsby, C. (2017). Modeling the isotopic evolution of snowpack and snowmelt: Testing a spatially distributed parsimonious approach. *Water Resources Research*, *53*(7), 5813–5830. https://doi.org/10.1002/2017wr020650

Ala-aho, P., Welker, J. M., Bailey, H., Højlund Pedersen, S., Kopec, B., Klein, E., et al. (2021). Arctic snow isotope hydrology: A comparative snow-water vapor study. *Atmosphere*, *12*(2), 150. https://doi.org/10.3390/atmos12020150

Allen, S. T., Brooks, R., Keim, R., Bond, B., & McDonnell, J. (2013). The role of pre-event canopy storage in throughfall and stemflow by using isotopic tracers. *Ecohydrology*, *7*(2), 858–868. https://doi.org/10.1002/eco.1408

Allen, S. T., Keim, R. F., Barnard, H. R., McDonnell, J. J., & Brooks, R. J. (2016). The role of stable isotopes in understanding rainfall interception processes: A review. *WIREs Water*, *4*(1), e1187. https://doi.org/10.1002/wat2.1187

Allen, S. T., Kirchner, J. W., Braun, S., Siegwolf, R. T. W., & Goldsmith, G. R. (2019). Seasonal origins of soil water used by trees. *Hydrology and Earth System Sciences*, *23*(2), 1199–1210. https://doi.org/10.5194/hess-23-1199-2019

Allen, S. T., Kirchner, J. W., & Goldsmith, G. R. (2018). Predicting spatial patterns in precipitation isotope (Δ^2H and Δ^{18}O) seasonality using sinusoidal isoscapes. *Geophysical Research Letters*, *45*(10), 4859–4868. https://doi.org/10.1029/2018gl077458

Allen, S. T., von Freyberg, J., Weiler, M., Goldsmith, G. R., & Kirchner, J. W. (2019). The seasonal origins of streamwater in Switzerland. *Geophysical Research Letters*, *46*(17–18), 10425–10434. https://doi.org/10.1029/2019GL084552

Angert, A., Cappa, C. D., & DePaolo, D. J. (2004). Kinetic ^{17}O effects in the hydrologic cycle: Indirect evidence and implications. *Geochimica et Cosmochimica Acta*, *68*(17), 3487–3495. https://doi.org/10.1016/j.gca.2004.02.010

Arellano, L. N., Good, S. P., Sánchez-Murillo, R., Jarvis, W. T., Noone, D. C., & Finkenbiner, C. E. (2020). Bayesian estimates of the mean recharge elevations of water sources in the Central America region using stable water isotopes. *Journal of Hydrology: Regional Studies*, *32*, 100739. https://doi.org/10.1016/j.ejrh.2020.100739

Azevedo da Silva, T., Ferreira do Rosário, F., & Cardoso da Silva Júnior, G. (2020). Environmental isotopes and hydrochemical tracers applied to hydrogeological conceptual modeling of the southwest portion of the Amazon Aquifer System (Acre, Brazil). *Applied Geochemistry*, *120*, 104670. https://doi.org/10.1016/j.apgeochem.2020.104670

Barthold, F. K., Tyralla, C., Schneider, K., Vaché, K. B., Frede, H. G., & Breuer, L. (2011). How many tracers do we need for end member mixing analysis (EMMA)? A sensitivity analysis. *Water Resources Research*, *47*(8), 1–14. https://doi.org/10.1029/2011WR010604

Bazemore, D. E., Eshleman, K. N., & Hollenbeck, K. J. (1994). The role of soil water in stormflow generation in a forested headwater catchment: Synthesis of natural tracer and hydrometric evidence. *Journal of Hydrology*, *162*(1–2), 47–75. https://doi.org/10.1016/0022-1694(94)90004-3

Begemann, F., & Libby, W. F. (1957). Continental water balance, ground water inventory and storage times, surface ocean mixing rates and world-wide water circulation patterns from cosmic-ray and bomb tritium. *Geochimica et Cosmochimica Acta*, *12*(4), 277–296. https://doi.org/10.1016/0016-7037(57)90040-6

Benettin, P., Nehemy, M. F., Asadollahi, M., Pratt, D., Bensimon, M., McDonnell, J. J., & Rinaldo, A. (2021). Tracing and closing the water balance in a vegetated lysimeter. *Water Resources Research*, *57*(4), e2020WR029049. https://doi.org/10.1029/2020wr029049

Benettin, P., Rodriguez, N. B., Sprenger, M., Kim, M., Klaus, J., Harman, C. J., et al. (2022). Transit time estimation in catchments: Recent developments and future directions. *Water Resources Research*, *58*(11), e2022WR033096. https://doi.org/10.1029/2022WR033096

Benettin, P., Volkmann, T. H. M., von Freyberg, J., Frentress, J., Penna, D., Dawson, T. E., & Kirchner, J. W. (2018). Effects of climatic seasonality on the isotopic composition of evaporating soil waters. *Hydrology and Earth System Sciences*, *22*(5), 2881–2890. https://doi.org/10.5194/hess-22-2881-2018

Beria, H., Larsen, J. R., Ceperley, N. C., Michelon, A., Vennemann, T., & Schaefli, B. (2018). Understanding snow hydrological processes through the lens of stable water isotopes. *WIREs Water*, *5*(6), e1311. https://doi.org/10.1002/wat2.1311

Beria, H., Larsen, J. R., Michelon, A., Ceperley, N. C., & Schaefli, B. (2020). HydroMix v1.0: A new Bayesian mixing framework for attributing uncertain hydrological sources. *Geoscientific Model Development*, *13*(5), 2433–2450. https://doi.org/10.5194/gmd-13-2433-2020

Beria, H., Nanda, T., Singh Bisht, D., & Chatterjee, C. (2017). Does the GPM mission improve the systematic error component in satellite rainfall estimates over TRMM? An evaluation at a pan-India scale. *Hydrology and Earth System Sciences*, *21*(12), 6117–6134. https://doi.org/10.5194/hess-21-6117-2017

Berkelhammer, M., Still, C. J., Ritter, F., Winnick, M., Anderson, L., Carroll, R., et al. (2020). Persistence and plasticity in conifer water-use strategies. *Journal of Geophysical Research: Biogeosciences*, *125*(2), e2018JG004845. https://doi.org/10.1029/2018JG004845

Berry, Z. C., Emery, N. C., Gotsch, S. G., & Goldsmith, G. R. (2018). Foliar water uptake: Processes, pathways, and integration into plant water budgets. *Plant, Cell and Environment*, *42*(2), 410–423. https://doi.org/10.1111/pce.13439

Bertrand, G., Masini, J., Goldscheider, N., Meeks, J., Lavastre, V., Celle-Jeanton, H., et al. (2012). Determination of spatiotemporal variability of tree water uptake using stable isotopes (Δ^{18}O, Δ^2H) in an alluvial system supplied by a high-altitude watershed, Pfyn forest, Switzerland. *Ecohydrology*, *7*(2), 319–333. https://doi.org/10.1002/eco.1347

Beven, K. (2006). A manifesto for the equifinality thesis. *Journal of Hydrology*, *320*(1–2), 18–36. https://doi.org/10.1016/j.jhydrol.2005.07.007

Beven, K., & Binley, A. (1992). The future of distributed models: Model calibration and uncertainty prediction. *Hydrological Processes*, *6*(3), 279–298. https://doi.org/10.1002/hyp.3360060305

Beyer, M., & Penna, D. (2021). On the spatio-temporal under-representation of isotopic data in ecohydrological studies. *Frontiers in Water*, *3*, 643013. https://doi.org/10.3389/frwa.2021.643013

Bhatia, M. P., Kujawinski, E. B., Das, S. B., Breier, C. F., Henderson, P. B., & Charette, M. A. (2013). Greenland meltwater as a significant and potentially bioavailable source of iron to the ocean. *Nature Geoscience*, *6*(4), 274–278. https://doi.org/10.1038/ngeo1746

Birkel, C., Correa Barahona, A., Duvert, C., Granados Bolaños, S., Chavarría Palma, A., Durán Quesada, A. M., et al. (2021). End member and Bayesian mixing models consistently indicate near-surface flowpath dominance in a pristine humid tropical rainforest. *Hydrological Processes*, *35*(4), e14153. https://doi.org/10.1002/hyp.14153

Bishop, K., Seibert, J., Köhler, S., & Laudon, H. (2004). Resolving the double paradox of rapidly mobilized old water with highly variable responses in runoff chemistry. *Hydrological Processes*, *18*(1), 185–189. https://doi.org/10.1002/hyp.5209

Blaen, P. J., Hannah, D. M., Brown, L. E., & Milner, A. M. (2014). Water source dynamics of high Arctic river basins. *Hydrological Processes*, *28*(10), 3521–3538. https://doi.org/10.1002/hyp.9891

Bowen, G. J., Ehleringer, J. R., Chesson, L. A., Stange, E., & Cerling, T. E. (2007). Stable isotope ratios of tap water in the contiguous United States. *Water Resources Research*, *43*(3). https://doi.org/10.1029/2006wr005186

Bowen, G. J., Putman, A., Brooks, R. J., Bowling, D. R., Oerter, E. J., & Good, S. P. (2018). Inferring the source of evaporated waters using stable H and O isotopes. *Oecologia*, *187*(4), 1025–1039. https://doi.org/10.1007/s00442-018-4192-5

Breuer, B., Klemm, O., Lai, Y.-J., Lin, P.-H., Meyer, H., Nieberding, F., & Song, Q.-H. (2021). Up and down: Bidirectional fluxes of fog droplets at two subtropical mountain forest sites. *Journal of Hydrology*, *601*, 126491. https://doi.org/10.1016/j.jhydrol.2021.126491

Brooks, R. J., Barnard, H. R., Coulombe, R., & McDonnell, J. J. (2010). Ecohydrologic separation of water between trees and streams in a Mediterranean climate. *Nature Geoscience*, *3*(2), 100–104. https://doi.org/10.1038/ngeo722

Brooks, R. J., Gibson, J. J., Birks, S. J., Weber, M. H., Rodecap, K. D., & Stoddard, J. L. (2014). Stable isotope estimates of evaporation: Inflow and water residence time for lakes across the United States as a tool for national lake water quality assessments. *Limnology & Oceanography*, *59*(6), 2150–2165. https://doi.org/10.4319/lo.2014.59.6.2150

Brooks, R. J., Wigington, P. J., Phillips, D. L., Comeleo, R., & Coulombe, R. (2012). Willamette river basin surface water isoscape (Δ^{18}O and Δ^{2}H): Temporal changes of source water within the river. *Ecosphere*, *3*(5), 1–21. https://doi.org/10.1890/es11-00338.1

Burns, D. A., & McDonnell, J. J. (1998). Effects of a beaver pond on runoff processes: Comparison of two headwater catchments. *Journal of Hydrology*, *205*(3–4), 248–264. https://doi.org/10.1016/s0022-1694(98)00081-x

Burns, D. A., McDonnell, J. J., Hooper, R. P., Peters, N. E., Freer, J. E., Kendall, C., & Beven, K. (2001). Quantifying contributions to storm runoff through end-member mixing analysis and hydrologic measurements at the Panola Mountain Research Watershed (Georgia, USA). *Hydrological Processes*, *15*(10), 1903–1924. https://doi.org/10.1002/hyp.246

Burt, E. I., Goldsmith, G. R., Cruz-de Hoyos, R. M., Ccahuana Quispe, A. J., & West, A. J. (2023). The seasonal origins and ages of water provisioning streams and trees in a tropical montane cloud forest. *Hydrology and Earth System Sciences*, *27*(22), 4173–4186. https://doi.org/10.5194/hess-27-4173-2023

Buttle, J. (1994). Isotope hydrograph separations and rapid delivery of pre-event water from drainage basins. *Progress in Physical Geography: Earth and Environment*, *18*(1), 16–41. https://doi.org/10.1177/030913339401800102

Cable, J., Ogle, K., & Williams, D. (2011). Contribution of glacier meltwater to streamflow in the Wind River Range, Wyoming, inferred via a Bayesian mixing model applied to isotopic measurements. *Hydrological Processes*, *25*(14), 2228–2236. https://doi.org/10.1002/hyp.7982

Campbell, J. L., & Green, M. B. (2019). *Water isotope samples from Watershed 3 at Hubbard Brook experimental forest, 2006–2010*. Environmental Data Initiative. https://doi.org/10.6073/pasta/f5740876b68ec42b695c39d8ad790cee

Carpenter, B., Gelman, A., Hoffman, M., Lee, D., Goodrich, B., Betancourt, M., et al. (2017). Stan: A probabilistic programming language. *Journal of Statistical Software, Articles*, *76*(1), 1–32. https://doi.org/10.18637/jss.v076.i01

Carrera, J., Vázquez-Suñé, E., Castillo, O., & Sánchez-Vila, X. (2004). A methodology to compute mixing ratios with uncertain end-members. *Water Resources Research*, *40*(12), 1–11. https://doi.org/10.1029/2003WR002263

Carrière, S. D., Martin-StPaul, N. K., Cakpo, C. B., Patris, N., Gillon, M., Chalikakis, K., et al. (2020). The role of deep vadose zone water in tree transpiration during drought periods in karst settings—Insights from isotopic tracing and leaf water potential. *Science of the Total Environment*, *699*, 134332. https://doi.org/10.1016/j.scitotenv.2019.134332

Carroll, R. W., Deems, J. S., Niswonger, R., Schumer, R., & Williams, K. H. (2019). The importance of interflow to groundwater recharge in a snowmelt-dominated headwater basin. *Geophysical Research Letters*, *46*(11), 5899–5908. https://doi.org/10.1029/2019GL082447

Carroll, R. W. H., Deems, J., Maxwell, R., Sprenger, M., Brown, W., Newman, A., et al. (2022). Variability in observed stable water isotopes in snowpack across a mountainous watershed in Colorado. *Hydrological Processes*, *36*(8), e14653. https://doi.org/10.1002/hyp.14653

Carroll, R. W. H., Deems, J., Sprenger, M., Maxwell, R., Brown, W., Newman, A., et al. (2022). Modeling snow dynamics and stable water isotopes across mountain landscapes. *Geophysical Research Letters*, *49*(20), e2022GL098780. https://doi.org/10.1029/2022gl098780

Cayuela, C., Llorens, P., Sánchez-Costa, E., & Latron, J. (2018). Modification of the isotopic composition of rainfall by throughfall and stemflow: The case of Scots pine and downy oak forests under Mediterranean conditions. *Ecohydrology*, *7*(2). https://doi.org/10.1002/eco.2025

Ceperley, N., Gimeno, T. E., Jacobs, S. R., Beyer, M., Dubbert, M., Fischer, B., et al. (2024). Toward a common methodological framework for the sampling, extraction, and isotopic analysis of water in the Critical Zone to study vegetation water use. *WIREs Water*, *11*(4), e1727. https://doi.org/10.1002/wat2.1727

Ceperley, N., Zuecco, G., Beria, H., Carturan, L., Michelon, A., Penna, D., et al. (2020). Seasonal snow cover decreases young water fractions in high alpine catchments. *Hydrological Processes*, *34*(25), 4794–4813. https://doi.org/10.1002/hyp.13937

Chazette, P., Flamant, C., Sodemann, H., Totems, J., Monod, A., Dieudonné, E., et al. (2021). Experimental investigation of the stable water isotope distribution in an Alpine lake environment (L-WAIVE). *Atmospheric Chemistry and Physics*, *21*(14), 10911–10937. https://doi.org/10.5194/acp-21-10911-2021

Christensen, J. N., Dafflon, B., Shiel, A. E., Tokunaga, T. K., Wan, J., Faybishenko, B., et al. (2018). Using strontium isotopes to evaluate the spatial variation of groundwater recharge. *Science of the Total Environment*, *637*(638), 672–685. https://doi.org/10.1016/j.scitotenv.2018.05.019

Christophersen, N., & Hooper, R. P. (1992). Multivariate analysis of stream water chemical data: The use of principal components analysis for the end-member mixing problem. *Water Resources Research*, *28*(1), 99–107. https://doi.org/10.1029/91WR02518

Christophersen, N., Neal, C., Hooper, R. P., Vogt, R. D., & Andersen, S. (1990). Modelling streamwater chemistry as a mixture of soilwater end-members—A step towards second-generation acidification models. *Journal of Hydrology*, *116*(1–4), 307–320. https://doi.org/10.1016/0022-1694(90)90130-P

Chung, M., Dufour, A., Pluche, R., & Thompson, S. (2017). How much does dry-season fog matter? Quantifying fog contributions to water balance in a coastal California watershed. *Hydrological Processes*, *31*(22), 3948–3961. https://doi.org/10.1002/hyp.11312

Clark, I. D., Douglas, M., Raven, K., & Bottomley, D. (2000). Recharge and preservation of Laurentide glacial melt water in the Canadian Shield. *Groundwater*, *38*(5), 735–742. https://doi.org/10.1111/j.1745-6584.2000.tb02709.x

Cole, A., & Boutt, D. F. (2021). Spatially-resolved integrated precipitation-surface-groundwater water isotope mapping from crowd sourcing: Toward understanding water cycling across a post-glacial landscape. *Frontiers in Water*, *3*, 645634. https://doi.org/10.3389/frwa.2021.645634

Cook, P., & Dogramaci, S. (2019). Estimating recharge from recirculated groundwater with dissolved gases: An end-member mixing analysis. *Water Resources Research*, *55*(7), 5468–5486. https://doi.org/10.1029/2019WR025012

Correa, A., Windhorst, D., Tetzlaff, D., Crespo, P., Célleri, R., Feyen, J., & Breuer, L. (2017). Temporal dynamics in dominant runoff sources and flow paths in the Andean Páramo. *Water Resources Research*, *53*(7), 5998–6017. https://doi.org/10.1002/2016wr020187

Cotte, G., & Vennemann, T. W. (2020). Mixing of Rhône River water in Lake Geneva: Seasonal tracing using stable isotope composition of water. *Journal of Great Lakes Research*, *46*(4), 839–849. https://doi.org/10.1016/j.jglr.2020.05.015

Couvreur, V., Rothfuss, Y., Meunier, F., Bariac, T., Biron, P., Durand, J.-L., et al. (2020). Disentangling temporal and population variability in plant root water uptake from stable isotopic analysis: When rooting depth matters in labeling studies. *Hydrology and Earth System Sciences*, *24*(6), 3057–3075. https://doi.org/10.5194/hess-24-3057-2020

Craig, H., & Gordon, L. I. (1965). Deuterium and oxygen 18 variations in the ocean and the marine atmosphere. In *Stable isotopes in oceanographic studies and paleotemperatures*. Laboratorio di Geologia Nucleare.

Crawford, J., Azcurra, C. S., Hughes, C. E., Gibson, J. J., & Parkes, S. D. (2019). Comparison of atmospheric water vapour Δ^{18}O and Δ^{2}H estimated using evaporation pan, rainfall equilibrium and continuous measurements. *Journal of Hydrology*, *576*, 551–560. https://doi.org/10.1016/j.jhydrol.2019.06.056

Dar, T., Rai, N., Kumar, S., & Bhat, M. A. (2024). Understanding hydrological processes of glacierized catchments in the western Himalayas by a multi-year tracer-based hydrograph separation analysis. *Hydrological Processes*, *38*(2), e15083. https://doi.org/10.1002/hyp.15083

Dawson, T. E. (1998). Fog in the California redwood forest: Ecosystem inputs and use by plants. *Oecologia*, *117*(4), 476–485. https://doi.org/10.1007/S004420050683
Dawson, T. E., & Ehleringer, J. R. (1991). Streamside trees that do not use stream water. *Nature*, *350*(6316), 335–337. https://doi.org/10.1038/350335a0
Deeds, J., Amirbahman, A., Norton, S. A., Suitor, D. G., & Bacon, L. C. (2021). Predicting anoxia in low-nutrient temperate lakes. *Ecological Applications*, *31*(6), e02361. https://doi.org/10.1002/eap.2361
Delsman, J. R., Oude Essink, G. H., Beven, K. J., & Stuyfzand, P. J. (2013). Uncertainty estimation of end-member mixing using generalized likelihood uncertainty estimation (GLUE), applied in a lowland catchment. *Water Resources Research*, *49*(8), 4792–4806. https://doi.org/10.1002/wrcr.20341
Dembélé, M., Hrachowitz, M., Savenije, H. H. G., Mariéthoz, G., & Schaefli, B. (2020). Improving the predictive skill of a distributed hydrological model by calibration on spatial patterns with multiple satellite data sets. *Water Resources Research*, *56*(1), e2019WR026085. https://doi.org/10.1029/2019WR026085
Dennedy-Frank, P. J., Visser, A., Maina, F. Z., & Siirila-Woodburn, E. R. (2024). Investigating mountain watershed headwater-to-groundwater connections, water sources, and storage selection behavior with dynamic-flux particle tracking. *Journal of Advances in Modeling Earth Systems*, *16*(8), e2023MS003976. https://doi.org/10.1029/2023ms003976
Derrien, M., Lee, M.-H., Choi, K., Lee, K.-S., & Hur, J. (2020). Tracking the evolution of particulate organic matter sources during summer storm events via end-member mixing analysis based on spectroscopic proxies. *Chemosphere*, *252*, 126445. https://doi.org/10.1016/j.chemosphere.2020.126445
de Wet, R. F., West, A. G., & Harris, C. (2020). Seasonal variation in tap water Δ^2H and Δ^{18}O isotopes reveals two tap water worlds. *Scientific Reports*, *10*(1), 13544. https://doi.org/10.1038/s41598-020-70317-2
Dietermann, N., & Weiler, M. (2013). Spatial distribution of stable water isotopes in alpine snow cover. *Hydrology and Earth System Sciences*, *17*(7), 2657–2668. https://doi.org/10.5194/hess-17-2657-2013
Dietrich, L. J., Steen-Larsen, H. C., Wahl, S., Jones, T. R., Town, M. S., & Werner, M. (2023). Snow-atmosphere humidity exchange at the ice sheet surface alters annual mean climate signals in ice core records. *Geophysical Research Letters*, *50*(20), e2023GL104249. https://doi.org/10.1029/2023GL104249
Dinçer, T. (1968). The use of oxygen 18 and deuterium concentrations in the water balance of lakes. *Water Resources Research*, *4*(6), 1289–1306. https://doi.org/10.1029/WR004i006p01289
Dong, J., Zhao, X., Liu, C., Huang, Z., Qadeer, A., Zhu, Y., et al. (2022). Multi-isotope tracing nitrate dynamics and sources during thermal stratification in a deep reservoir. *Chemosphere*, *307*, 135816. https://doi.org/10.1016/j.chemosphere.2022.135816
Dubbert, M., Cuntz, M., Piayda, A., Maguás, C., & Werner, C. (2013). Partitioning evapotranspiration—Testing the Craig and Gordon model with field measurements of oxygen isotope ratios of evaporative fluxes. *Journal of Hydrology*, *496*, 142–153. https://doi.org/10.1016/j.jhydrol.2013.05.033
Durand, P., & Torres, J. J. (1996). Solute transfer in agricultural catchments: The interest and limits of mixing models. *Journal of Hydrology*, *181*(1–4), 1–22. https://doi.org/10.1016/0022-1694(95)02922-2
Dwivedi, R., Meixner, T., McIntosh, J. C., Ferré, P. T., Eastoe, C. J., Niu, G., et al. (2019). Hydrologic functioning of the deep critical zone and contributions to streamflow in a high-elevation catchment: Testing of multiple conceptual models. *Hydrological Processes*, *33*(4), 476–494. https://doi.org/10.1002/hyp.13363
Enemark, T., Peeters, L. J., Mallants, D., & Batelaan, O. (2019). Hydrogeological conceptual model building and testing: A review. *Journal of Hydrology*, *569*, 310–329. https://doi.org/10.1016/j.jhydrol.2018.12.007
Engel, M., Frentress, J., Penna, D., Andreoli, A., van Meerveld, I., Zerbe, S., et al. (2022). How do geomorphic characteristics affect the source of tree water uptake in restored river floodplains? *Ecohydrology*, *15*(4), e2443. https://doi.org/10.1002/eco.2443
Engel, M., Penna, D., Bertoldi, G., Dell'Agnese, A., Soulsby, C., & Comiti, F. (2015). Identifying run-off contributions during melt-induced run-off events in a glacierized alpine catchment. *Hydrological Processes*, *30*(3), 343–364. https://doi.org/10.1002/hyp.10577
Erhardt, E. B., & Bedrick, E. J. (2012). A Bayesian framework for stable isotope mixing models. *Environmental and Ecological Statistics*, *20*(3), 377–397. https://doi.org/10.1007/s10651-012-0224-1
Evaristo, J., & McDonnell, J. J. (2017). Prevalence and magnitude of groundwater use by vegetation: A global stable isotope meta-analysis. *Scientific Reports*, *7*(1), 44110. https://doi.org/10.1038/srep44110
Famiglietti, J. S. (2014). The global groundwater crisis. *Nature Climate Change*, *4*(11), 945–948. https://doi.org/10.1038/nclimate2425
Feher, R., Voiculescu, M., Chiroiu, P., & Persoiu, A. (2021). The stable isotope composition of hoarfrost. *Isotopes in Environmental and Health Studies*, *57*(4), 386–399. https://doi.org/10.1080/10256016.2021.1917567
Feng, X., Taylor, S., Renshaw, C. E., & Kirchner, J. W. (2002). Isotopic evolution of snowmelt 1. A physically based one-dimensional model. *Water Resources Research*, *38*(10). https://doi.org/10.1029/2001wr000814
Fischer, B. M., van Meerveld, H. I., & Seibert, J. (2017). Spatial variability in the isotopic composition of rainfall in a small headwater catchment and its effect on hydrograph separation. *Journal of Hydrology*, *547*, 755–769. https://doi.org/10.1016/j.jhydrol.2017.01.045
Floriancic, M. G., Allen, S., & Kirchner, J. W. (2024). Isotopic evidence for seasonal water sources in tree xylem and forest soils. *Ecohydrology*, *17*(5), e2641. https://doi.org/10.1002/eco.2641
Forstner, V., Groh, J., Vremec, M., Herndl, M., Vereecken, H., Gerke, H. H., et al. (2021). Response of water fluxes and biomass production to climate change in permanent grassland soil ecosystems. *Hydrology and Earth System Sciences*, *25*(12), 6087–6106. https://doi.org/10.5194/hess-25-6087-2021
Froehlich, K., Kralik, M., Papesch, W., Rank, D., Scheifinger, H., & Stichler, W. (2008). Deuterium excess in precipitation of Alpine regions—Moisture recycling. *Isotopes in Environmental and Health Studies*, *44*(1), 61–70. https://doi.org/10.1080/10256010801887208
Gai, H., Shi, P., & Li, Z. (2023). Untangling the uncertainties in plant water source partitioning with isotopes. *Water Resources Research*, *59*(12), e2022WR033849. https://doi.org/10.1029/2022WR033849
Gat, J. R., & Tzur, Y. (1967). *Modification of the isotopic composition of rainwater by processes which occur before groundwater recharge*. International Atomic Energy Agency (IAEA). Vienna, Austria.
Genereux, D. (1998). Quantifying uncertainty in tracer-based hydrograph separations. *Water Resources Research*, *34*(4), 915–919. https://doi.org/10.1029/98wr00010
Gessler, A., Bächli, L., Rouholahnejad Freund, E., Treydte, K., Schaub, M., Haeni, M., et al. (2021). Drought reduces water uptake in beech from the drying topsoil, but no compensatory uptake occurs from deeper soil layers. *New Phytologist*, *233*(1), 194–206. https://doi.org/10.1111/nph.17767

Gibson, J., Birks, S., Yi, Y., Moncur, M., & McEachern, P. (2016). Stable isotope mass balance of fifty lakes in central Alberta: Assessing the role of water balance parameters in determining trophic status and lake level. *Journal of Hydrology: Regional Studies*, *6*, 13–25. https://doi.org/10.1016/j.ejrh.2016.01.034

Gibson, J. J., & Edwards, T. W. D. (2002). Regional water balance trends and evaporation-transpiration partitioning from a stable isotope survey of lakes in northern Canada. *Global Biogeochemical Cycles*, *16*(2), 10-1–10-14. https://doi.org/10.1029/2001GB001839

Gibson, J. J., Edwards, T. W. D., & Prowse, T. D. (1996). Development and validation of an isotopic method for estimating lake evaporation. *Hydrological Processes*, *10*(10), 1369–1382. https://doi.org/10.1002/(SICI)1099-1085(199610)10:10⟨1369::AID-HYP467⟩3.0.CO;2-J

Goldsmith, G. R., Allen, S. T., Braun, S., Siegwolf, R. T. W., & Kirchner, J. W. (2022). Climatic influences on summer use of winter precipitation by trees. *Geophysical Research Letters*, *49*(10), e2022GL098323. https://doi.org/10.1029/2022GL098323

Good, S. P., Mallia, D. V., Lin, J. C., & Bowen, G. J. (2014). Stable isotope analysis of precipitation samples obtained via crowdsourcing reveals the spatiotemporal evolution of Superstorm Sandy. *PLoS One*, *9*(3), e91117. https://doi.org/10.1371/journal.pone.0091117

Good, S. P., Soderberg, K., Guan, K., King, E. G., Scanlon, T. M., & Caylor, K. K. (2014). Δ^2H isotopic flux partitioning of evapotranspiration over a grass field following a water pulse and subsequent dry down. *Water Resources Research*, *50*(2), 1410–1432. https://doi.org/10.1002/2013WR014333

Gracz, M. B., Moffett, M. F., Siegel, D. I., & Glaser, P. H. (2015). Analyzing peatland discharge to streams in an Alaskan watershed: An integration of end-member mixing analysis and a water balance approach. *Journal of Hydrology*, *530*, 667–676. https://doi.org/10.1016/j.jhydrol.2015.09.072

Granger, S. J., Bol, R., Meier-Augenstein, W., Leng, M. J., Kemp, H. F., Heaton, T. H. E., & White, S. M. (2010). The hydrological response of heavy clay grassland soils to rainfall in south-west England using Δ^2H. *Rapid Communications in Mass Spectrometry*, *24*(5), 475–482. https://doi.org/10.1002/rcm.4281

Gribbin, T., Mackay, J. D., MacDonald, A., Hannah, D. M., Buytaert, W., Baiker, J. R., et al. (2024). Bofedal wetland and glacial melt contributions to dry season streamflow in a high-Andean headwater watershed. *Hydrological Processes*, *38*(8), e15237. https://doi.org/10.1002/hyp.15237

Groh, J., Pütz, T., Gerke, H. H., Vanderborght, J., & Vereecken, H. (2019). Quantification and prediction of nighttime evapotranspiration for two distinct grassland ecosystems. *Water Resources Research*, *55*(4), 2961–2975. https://doi.org/10.1029/2018wr024072

Groh, J., Slawitsch, V., Herndl, M., Graf, A., Vereecken, H., & Pütz, T. (2018). Determining dew and hoar frost formation for a low mountain range and alpine grassland site by weighable lysimeter. *Journal of Hydrology*, *563*, 372–381. https://doi.org/10.1016/j.jhydrol.2018.06.009

Hall, C. A., Saia, S. M., Popp, A. L., Dogulu, N., Schymanski, S. J., Drost, N., et al. (2022). A hydrologist's guide to open science. *Hydrology and Earth System Sciences*, *26*(3), 647–664. https://doi.org/10.5194/hess-26-647-2022

Hatvani, I. G., Szatmári, G., Kern, Z., Erdélyi, D., Vreča, P., Kanduč, T., et al. (2021). Geostatistical evaluation of the design of the precipitation stable isotope monitoring network for Slovenia and Hungary. *Environment International*, *146*, 106263. https://doi.org/10.1016/j.envint.2020.106263

Hayashi, M., Van Der Kamp, G., & Rosenberry, D. O. (2016). Hydrology of Prairie Wetlands: Understanding the integrated surface-water and groundwater processes. *Wetlands*, *36*(S2), 237–254. https://doi.org/10.1007/s13157-016-0797-9

He, Z., Duethmann, D., & Tian, F. (2021). A meta-analysis based review of quantifying the contributions of runoff components to streamflow in glacierized basins. *Journal of Hydrology*, *603*, 126890. https://doi.org/10.1016/j.jhydrol.2021.126890

He, Z., Unger-Shayesteh, K., Vorogushyn, S., Weise, S. M., Duethmann, D., Kalashnikova, O., et al. (2020). Comparing Bayesian and traditional end-member mixing approaches for hydrograph separation in a glacierized basin. *Hydrology and Earth System Sciences*, *24*(6), 3289–3309. https://doi.org/10.5194/hess-24-3289-2020

Herrera, C., Custodio, E., Chong, G., Lambán, L. J., Riquelme, R., Wilke, H., et al. (2016). Groundwater flow in a closed basin with a saline shallow lake in a volcanic area: Laguna Tuyajto, northern Chilean Altiplano of the Andes. *Science of the Total Environment*, *541*, 303–318. https://doi.org/10.1016/j.scitotenv.2015.09.060

Holloway-Phillips, M., Cernusak, L. A., Barbour, M., Song, X., Cheesman, A., Munksgaard, N., et al. (2016). Leaf vein fraction influences the Péclet effect and ^{18}O enrichment in leaf water. *Plant, Cell and Environment*, *39*(11), 2414–2427. https://doi.org/10.1111/pce.12792

Holmes, T. L., Stadnyk, T. A., Asadzadeh, M., & Gibson, J. J. (2023). Guidance on large scale hydrologic model calibration with isotope tracers. *Journal of Hydrology*, *621*, 129604. https://doi.org/10.1016/J.JHYDROL.2023.129604

Hooper, R. P. (2003). Diagnostic tools for mixing models of stream water chemistry. *Water Resources Research*, *39*(3), 55–61. https://doi.org/10.1029/2002WR001528

Hooper, R. P., Christophersen, N., & Peters, N. E. (1990). Modelling streamwater chemistry as a mixture of soilwater end-members—An application to the Panola Mountain catchment, Georgia, U.S.A. *Journal of Hydrology*, *116*(1–4), 321–343. https://doi.org/10.1016/0022-1694(90)90131-G

Hürkamp, K., Zentner, N., Reckerth, A., Weishaupt, S., Wetzel, K.-F., Tschiersch, J., & Stumpp, C. (2018). Spatial and Temporal Variability of Snow Isotopic Composition on Mt. Zugspitze, Bavarian Alps, Germany. *Journal of Hydrology and Hydromechanics*, *67*(1), 49–58. https://doi.org/10.2478/johh-2018-0019

IAEA. (2023). *Towards best practices in isotope-enabled hydrological modelling applications (No. 2022)*. International Atomic Energy Agency. Vienna Retrieved from https://www.iaea.org/publications/15290/towards-best-practices-in-isotope-enabled-hydrological-modelling-applications

Imig, A., Augustin, L., Groh, J., Pütz, T., Zhou, T., Einsiedl, F., & Rein, A. (2023). Fate of herbicides in cropped lysimeters: 1. Influence of different processes and model structure on vadose zone flow. *Vadose Zone Journal*, *22*(5), e20265. https://doi.org/10.1002/vzj2.20265

Iorgulescu, I., Beven, K. J., & Musy, A. (2007). Flow, mixing, and displacement in using a data-based hydrochemical model to predict conservative tracer data. *Water Resources Research*, *43*(3). https://doi.org/10.1029/2005wr004019

Isiorho, S. A., & Matisof, G. (1990). Groundwater recharge from Lake Chad. *Limnology & Oceanography*, *35*(4), 931–938. https://doi.org/10.4319/lo.1990.35.4.0931

Isokangas, E., Rozanski, K., Rossi, P. M., Ronkanen, A.-K., & Kløve, B. (2015). Quantifying groundwater dependence of a sub-polar lake cluster in Finland using an isotope mass balance approach. *Hydrology and Earth System Sciences*, *19*(3), 1247–1262. https://doi.org/10.5194/hess-19-1247-2015

James, A. L., & Roulet, N. T. (2006). Investigating the applicability of end-member mixing analysis (EMMA) across scale: A study of eight small, nested catchments in a temperate forested watershed. *Water Resources Research*, *42*(8). https://doi.org/10.1029/2005wr004419

Jasechko, S. (2019). Global Isotope Hydrogeology—Review. *Reviews of Geophysics*, *57*(3), 835–965. https://doi.org/10.1029/2018RG000627

Jasechko, S., Birks, S. J., Gleeson, T., Wada, Y., Fawcett, P. J., Sharp, Z. D., et al. (2014). The pronounced seasonality of global groundwater recharge. *Water Resources Research*, *50*(11), 8845–8867. https://doi.org/10.1002/2014WR015809

Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R. G., et al. (2024). Rapid groundwater decline and some cases of recovery in aquifers globally. *Nature*, *625*(7996), 715–721. https://doi.org/10.1038/s41586-023-06879-8

Jasechko, S., Sharp, Z. D., Gibson, J. J., Birks, S. J., Yi, Y., & Fawcett, P. J. (2013). Terrestrial water fluxes dominated by transpiration. *Nature*, *496*(7445), 347–350. https://doi.org/10.1038/nature11983

Jasechko, S., & Taylor, R. G. (2015). Intensive rainfall recharges tropical groundwaters. *Environmental Research Letters*, *10*(12), 124015. https://doi.org/10.1088/1748-9326/10/12/124015

Jeelani, G., Shah, R. A., Deshpande, R. D., Fryar, A. E., Perrin, J., & Mukherjee, A. (2017). Distinguishing and estimating recharge to karst springs in snow and glacier dominated mountainous basins of the western Himalaya, India. *Journal of Hydrology*, *550*, 239–252. https://doi.org/10.1016/j.jhydrol.2017.05.001

Jiang, D., & Wang, K. (2019). The role of satellite-based remote sensing in improving simulated streamflow: A review. *Water*, *11*(8), 1615. https://doi.org/10.3390/w11081615

Jiménez-Rodríguez, C. D., Coenders-Gerrits, M., Wenninger, J., Gonzalez-Angarita, A., & Savenije, H. (2020). Contribution of understory evaporation in a tropical wet forest during the dry season. *Hydrology and Earth System Sciences*, *24*(4), 2179–2206. https://doi.org/10.5194/hess-24-2179-2020

Joerin, C., Beven, K., Iorgulescu, I., & Musy, A. (2002). Uncertainty in hydrograph separations based on geochemical mixing models. *Journal of Hydrology*, *255*(1–4), 90–106. https://doi.org/10.1016/s0022-1694(01)00509-1

Johnson, N. M., Likens, G. E., Bormann, F. H., Fisher, D. W., & Pierce, R. S. (1969). A Working Model for the Variation in Stream Water Chemistry at the Hubbard Brook Experimental Forest, New Hampshire. *Water Resources Research*, *5*(6), 1353–1363. https://doi.org/10.1029/wr005i006p01353

Jung, H., Tetzlaff, D., Birkel, C., & Soulsby, C. (2025). Recent developments and emerging challenges in tracer-aided modeling. *WIREs Water*, *12*(2), e70015. https://doi.org/10.1002/wat2.70015

Kaseke, K. F., Mills, A. J., Brown, R., Esler, K. J., Henschel, J. R., & Seely, M. K. (2012). A method for direct assessment of the "non rainfall" atmospheric water cycle: Input and evaporation from the soil. *Pure and Applied Geophysics*, *169*(5–6), 847–857. https://doi.org/10.1007/s00024-011-0328-9

Kaseke, K. F., Mills, A. J., Esler, K., Henschel, J., Seely, M. K., & Brown, R. (2012). Spatial variation of "non-rainfall" water input and the effect of mechanical soil crusts on input and evaporation. *Pure and Applied Geophysics*, *169*(12), 2217–2229. https://doi.org/10.1007/s00024-012-0469-5

Kaseke, K. F., Wang, L., & Seely, M. K. (2017). Nonrainfall water origins and formation mechanisms. *Science Advances*, *3*(3), e1603131. https://doi.org/10.1126/sciadv.1603131

Kaseke, K. F., Wang, L., Wanke, H., Tian, C., Lanning, M., & Jiao, W. (2018). Precipitation origins and key drivers of precipitation isotope (^{18}O, ^{2}H, and ^{17}O) compositions over Windhoek. *Journal of Geophysical Research: Atmospheres*, *123*(14), 7311–7330. https://doi.org/10.1029/2018JD028470

Kiewiet, L., von Freyberg, J., & van Meerveld, H. I. (2019). Spatiotemporal variability in hydrochemistry of shallow groundwater in a small pre-alpine catchment: The importance of landscape elements. *Hydrological Processes*, *33*(19), 2502–2522. https://doi.org/10.1002/hyp.13517

Kirchner, J. W. (2003). A double paradox in catchment hydrology and geochemistry. *Hydrological Processes*, *17*(4), 871–874. https://doi.org/10.1002/hyp.5108

Kirchner, J. W. (2019). Quantifying new water fractions and transit time distributions using ensemble hydrograph separation: Theory and benchmark tests. *Hydrology and Earth System Sciences*, *23*(1), 303–349. https://doi.org/10.5194/hess-23-303-2019

Kirchner, J. W. (2020). EndSplit EnviDat. https://doi.org/10.16904/envidat.91

Kirchner, J. W. (2023). Mixing models with multiple, overlapping, or incomplete end-members, quantified using time series of a single tracer. *Geophysical Research Letters*, *50*(12), e2023GL104147. https://doi.org/10.1029/2023gl104147

Kirchner, J. W., & Allen, S. T. (2020). Seasonal partitioning of precipitation between streamflow and evapotranspiration, inferred from end-member splitting analysis. *Hydrology and Earth System Sciences*, *24*(1), 17–39. https://doi.org/10.5194/hess-24-17-2020

Kirchner, J. W., & Knapp, J. L. A. (2020). Technical note: Calculation scripts for ensemble hydrograph separation. *Hydrology and Earth System Sciences*, *24*(11), 5539–5558. https://doi.org/10.5194/hess-24-5539-2020

Klaus, J., & McDonnell, J. (2013). Hydrograph separation using stable isotopes: Review and evaluation. *Journal of Hydrology*, *505*, 47–64. https://doi.org/10.1016/j.jhydrol.2013.09.006

Knapp, J. L. A., Neal, C., Schlumpf, A., Neal, M., & Kirchner, J. W. (2019). New water fractions and transit time distributions at plynlimon, wales, estimated from stable water isotopes in precipitation and streamflow. *Hydrology and Earth System Sciences*, *23*(10), 4367–4388. https://doi.org/10.5194/hess-23-4367-2019

Knighton, J., Fricke, E., Evaristo, J., de Boer, H. J., & Wassen, M. J. (2021). Phylogenetic underpinning of groundwater use by trees. *Geophysical Research Letters*, *48*(18), e2021GL093858. https://doi.org/10.1029/2021gl093858

Knoben, W. J. M., Clark, M. P., Bales, J., Bennett, A., Gharari, S., Marsh, C. B., et al. (2022). Community workflows to advance reproducibility in hydrologic modeling: Separating model-agnostic and model-specific configuration steps in applications of large-domain hydrologic models. *Water Resources Research*, *58*(11), e2021WR031753. https://doi.org/10.1029/2021WR031753

Koeniger, P., Gaj, M., Beyer, M., & Himmelsbach, T. (2016). Review on soil water isotope-based groundwater recharge estimations. *Hydrological Processes*, *30*(16), 2817–2834. https://doi.org/10.1002/hyp.10775

Koeniger, P., Hubbart, J. A., Link, T., & Marshall, J. D. (2008). Isotopic variation of snow cover and streamflow in response to changes in canopy structure in a snow-dominated mountain catchment. *Hydrological Processes*, *22*(4), 557–566. https://doi.org/10.1002/hyp.6967

Kohfahl, C., Sprenger, C., Herrera, J. B., Meyer, H., Chacón, F. F., & Pekdeger, A. (2008). Recharge sources and hydrogeochemical evolution of groundwater in semiarid and karstic environments: A field study in the Granada basin (southern Spain). *Applied Geochemistry*, *23*(4), 846–862. https://doi.org/10.1016/j.apgeochem.2007.09.009

Kulmatiski, A., Adler, P. B., Stark, J. M., & Tredennick, A. T. (2017). Water and nitrogen uptake are better associated with resource availability than root biomass. *Ecosphere*, *8*(3), e01738. https://doi.org/10.1002/ecs2.1738

Kuppel, S., Tetzlaff, D., Maneta, M. P., & Soulsby, C. (2018). EcH2O-iso 1.0: Water isotopes and age tracking in a process-based, distributed ecohydrological model. *Geoscientific Model Development*, *11*(7), 3045–3069. https://doi.org/10.5194/gmd-11-3045-2018

Lamontagne-Hallé, P., McKenzie, J. M., Kurylyk, B. L., & Zipper, S. C. (2018). Changing groundwater discharge dynamics in permafrost regions. *Environmental Research Letters*, *13*(8), 084017. https://doi.org/10.1088/1748-9326/aad404

Laudon, H., Hemond, H. F., Krouse, R., & Bishop, K. H. (2002). Oxygen 18 fractionation during snowmelt: Implications for spring flood hydrograph separation. *Water Resources Research*, *38*(11), 10–40. https://doi.org/10.1029/2002WR001510

Leibundgut, C., Maloszewski, P., & Külls, C. (2009). *Tracers in hydrology*. Wiley-Blackwell. Chichester.

Lekouch, I., Lekouch, K., Muselli, M., Mongruel, A., Kabbachi, B., & Beysens, D. (2012). Rooftop dew, fog and rain collection in southwest Morocco and predictive dew modeling using neural networks. *Journal of Hydrology*, *448–449*, 60–72. https://doi.org/10.1016/j.jhydrol.2012.04.004

Lewandowski, J., Meinikmann, K., Nützmann, G., & Rosenberry, D. O. (2015). Groundwater—The disregarded component in lake water and nutrient budgets. Part 2: Effects of groundwater on nutrients. *Hydrological Processes*, *29*(13), 2922–2955. https://doi.org/10.1002/hyp.10384

Li, Y., Aemisegger, F., Riedl, A., Buchmann, N., & Eugster, W. (2021). The role of dew and radiation fog inputs in the local water cycling of a temperate grassland during dry spells in central Europe. *Hydrology and Earth System Sciences*, *25*(5), 2617–2648. https://doi.org/10.5194/hess-25-2617-2021

Liebhard, G., Klik, A., Stumpp, C., Morales Santos, A., Eitzinger, J., & Nolz, R. (2022). Estimation of evaporation and transpiration rates under varying water availability for improving crop management of soybeans using oxygen isotope ratios of pore water. *International Agrophysics*, *36*(3), 181–195. https://doi.org/10.31545/intagr/150811

Liebhard, G., Klik, A., Stumpp, C., & Nolz, R. (2022). Partitioning evapotranspiration using water stable isotopes and information from lysimeter experiments. *Hydrological Sciences Journal*, *67*(4), 646–661. https://doi.org/10.1080/02626667.2022.2030866

Liu, Z., Yao, Z., & Wang, R. (2015). Contribution of glacial melt to river runoff as determined by stable isotopes at the source region of the Yangtze River, China. *Hydrology Research*, *47*(2), 442–453. https://doi.org/10.2166/nh.2015.089

Lone, A., Jeelani, G., Deshpande, R., & Padhya, V. (2021). Estimating the sources of stream water in snow dominated catchments of western Himalayas. *Advances in Water Resources*, *155*, 103995. https://doi.org/10.1016/j.advwatres.2021.103995

Lone, S. A., Jeelani, G., Deshpande, R., Mukherjee, A., Jasechko, S., & Lone, A. (2021). Meltwaters dominate groundwater recharge in cold arid desert of Upper Indus River Basin (UIRB), western Himalayas. *Science of the Total Environment*, *786*, 147514. https://doi.org/10.1016/j.scitotenv.2021.147514

Lone, S. A., Jeelani, G., Deshpande, R. D., & Shah, R. A. (2017). Evaluating the sensitivity of glacier to climate by using stable water isotopes and remote sensing. *Environmental Earth Sciences*, *76*(17), 598. https://doi.org/10.1007/s12665-017-6937-6

Luo, Z., Guan, H., Zhang, X., Xu, X., Dai, J., & Hua, M. (2019). Examination of the ecohydrological separation hypothesis in a humid subtropical area: Comparison of three methods. *Journal of Hydrology*, *571*, 642–650. https://doi.org/10.1016/j.jhydrol.2019.02.019

Malik, F. T., Clement, R. M., Gethin, D. T., Beysens, D., Cohen, R. E., Krawszik, W., & Parker, A. R. (2015). Dew harvesting efficiency of four species of cacti. *Bioinspiration & Biomimetics*, *10*(3), 036005. https://doi.org/10.1088/1748-3190/10/3/036005

Martin, J., Looker, N., Hoylman, Z., Jencso, K., & Hu, J. (2018). Differential use of winter precipitation by upper and lower elevation Douglas fir in the Northern Rockies. *Global Change Biology*, *24*(12), 5607–5621. https://doi.org/10.1111/gcb.14435

Martínez-de la Torre, A., & Miguez-Macho, G. (2019). Groundwater influence on soil moisture memory and land–atmosphere fluxes in the Iberian Peninsula. *Hydrology and Earth System Sciences*, *23*(12), 4909–4932. https://doi.org/10.5194/hess-23-4909-2019

Marttila, H., Lohila, A., Ala-Aho, P., Noor, K., Welker, J. M., Croghan, D., et al. (2021). Subarctic catchment water storage and carbon cycling—Leading the way for future studies using integrated datasets at Pallas, Finland. *Hydrological Processes*, *35*(9), e14350. https://doi.org/10.1002/hyp.14350

Masse-Dufresne, J., Barbecot, F., Baudron, P., & Gibson, J. (2021). Quantifying floodwater impacts on a lake water budget via volume-dependent transient stable isotope mass balance. *Hydrology and Earth System Sciences*, *25*(6), 3731–3757. https://doi.org/10.5194/hess-25-3731-2021

Massoud, E. C., Hoffman, F., Shi, Z., Tang, J., Alhajjar, E., Barnes, M., et al. (2023). Perspectives on artificial intelligence for predictions in ecohydrology. *Artificial Intelligence for the Earth Systems*, *2*(4). https://doi.org/10.1175/AIES-D-23-0005.1

Maurya, A. S., Shah, M., Deshpande, R. D., Bhardwaj, R. M., Prasad, A., & Gupta, S. K. (2010). Hydrograph separation and precipitation source identification using stable water isotopes and conductivity: River Ganga at Himalayan foothills. *Hydrological Processes*, *25*(10), 1521–1530. https://doi.org/10.1002/hyp.7912

McDonnell, J., Stewart, M., & Owens, I. (1991). Effect of catchment-scale subsurface mixing on stream isotopic response. *Water Resources Research*, *27*(12), 3065–3073. https://doi.org/10.1029/91wr02025

McGlynn, B. L., & McDonnell, J. J. (2003). Quantifying the relative contributions of riparian and hillslope zones to catchment runoff. *Water Resources Research*, *39*(11). https://doi.org/10.1029/2003wr002091

McHale, M. R., McDonnell, J. J., Mitchell, M. J., & Cirmo, C. P. (2002). A field-based study of soil water and groundwater nitrate release in an Adirondack forested watershed. *Water Resources Research*, *38*(4). https://doi.org/10.1029/2000wr000102

Meissner, R., Seeger, J., Rupp, H., Seyfarth, M., & Borg, H. (2007). Measurement of dew, fog, and rime with a high-precision gravitation lysimeter. *Journal of Plant Nutrition and Soil Science*, *170*(3), 335–344. https://doi.org/10.1002/jpln.200625002

Mercer, J. J. (2018). Insights into mountain wetland resilience to climate change: An evaluation of the hydrological processes contributing to the hydrodynamics of alpine wetlands in the Canadian Rocky Mountains Thesis (p. 76). https://doi.org/10.13140/RG.2.2.12825.47205

Michel, A., Brauchli, T., Lehning, M., Schaefli, B., & Huwald, H. (2020). Stream temperature and discharge evolution in Switzerland over the last 50 years: Annual and seasonal behaviour. *Hydrology and Earth System Sciences*, *24*(1), 115–142. https://doi.org/10.5194/hess-24-115-2020

Michelon, A., Ceperley, N., Beria, H., Larsen, J., Vennemann, T., & Schaefli, B. (2023). Hydrodynamics of a high alpine catchment characterized by four natural tracers. *Hydrology and Earth System Sciences*, *27*(7), 1403–1430. https://doi.org/10.5194/hess-27-1403-2023

Miller, S. A., Mercer, J. J., Lyon, S. W., Williams, D. G., & Miller, S. N. (2021). Stable isotopes of water and specific conductance reveal complimentary information on streamflow generation in snowmelt-dominated, seasonally arid watersheds. *Journal of Hydrology*, *596*, 126075. https://doi.org/10.1016/j.jhydrol.2021.126075

Muhic, F., Ala-Aho, P., Noor, K., Welker, J. M., Klöve, B., & Marttila, H. (2023). Flushing or mixing? Stable water isotopes reveal differences in arctic forest and peatland soil water seasonality. *Hydrological Processes*, *37*(1), e14811. https://doi.org/10.1002/hyp.14811

Müller, T., Lane, S. N., & Schaefli, B. (2022). Towards a hydrogeomorphological understanding of proglacial catchments: An assessment of groundwater storage and release in an alpine catchment. *Hydrology and Earth System Sciences*, *26*(23), 6029–6054. https://doi.org/10.5194/hess-26-6029-2022

Nehemy, M. F., Maillet, J., Perron, N., Pappas, C., Sonnentag, O., Baltzer, J. L., et al. (2022). Snowmelt water use at transpiration onset: Phenology, isotope tracing, and tree water transit time. *Water Resources Research*, *58*(9), e2022WR032344. https://doi.org/10.1029/2022wr032344

Nelson, D. B., Basler, D., & Kahmen, A. (2021). Precipitation isotope time series predictions from machine learning applied in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(26), e2024107118. https://doi.org/10.1073/pnas.2024107118

Njue, N., Stenfert Kroese, J., Gräf, J., Jacobs, S., Weeser, B., Breuer, L., & Rufino, M. (2019). Citizen science in hydrological monitoring and ecosystem services management: State of the art and future prospects. *Science of the Total Environment*, *693*, 133531. https://doi.org/10.1016/j.scitotenv.2019.07.337

Noor, K., Marttila, H., Klöve, B., Welker, J. M., & Ala-aho, P. (2023). The spatiotemporal variability of snowpack and snowmelt water Δ^{18}O and Δ^{2}H isotopes in a subarctic catchment. *Water Resources Research*, *59*(1), e2022WR033101. https://doi.org/10.1029/2022wr033101

Ohlanders, N., Rodriguez, M., & McPhee, J. (2013). Stable water isotope variation in a Central Andean watershed dominated by glacier and snowmelt. *Hydrology and Earth System Sciences*, *17*(3), 1035–1050. https://doi.org/10.5194/hess-17-1035-2013

Orlowski, N., Rinderer, M., Dubbert, M., Ceperley, N., Hrachowitz, M., Gessler, A., et al. (2023). Challenges in studying water fluxes within the soil-plant-atmosphere continuum: A tracer-based perspective on pathways to progress. *Science of the Total Environment*, *881*, 163510. https://doi.org/10.1016/j.scitotenv.2023.163510

Pärn, J., Raidla, V., Vaikmäe, R., Martma, T., Ivask, J., Mokrik, R., & Erg, K. (2016). The recharge of glacial meltwater and its influence on the geochemical evolution of groundwater in the Ordovician-Cambrian aquifer system, northern part of the Baltic Artesian Basin. *Applied Geochemistry*, *72*, 125–135. https://doi.org/10.1016/j.apgeochem.2016.07.007

Parnell, A. C., Inger, R., Bearhop, S., & Jackson, A. L. (2010). Source partitioning using stable isotopes: Coping with too much variation. *PLoS One*, *5*(3), e9672. https://doi.org/10.1371/journal.pone.0009672

Penna, D., Engel, M., Bertoldi, G., & Comiti, F. (2017). Towards a tracer-based conceptualization of meltwater dynamics and streamflow response in a glacierized catchment. *Hydrology and Earth System Sciences*, *21*(1), 23–41. https://doi.org/10.5194/hess-21-23-2017

Penna, D., Engel, M., Mao, L., Dell'Agnese, A., Bertoldi, G., & Comiti, F. (2014). Tracer-based analysis of spatial and temporal variations of water sources in a glacierized catchment. *Hydrology and Earth System Sciences*, *18*(12), 5271–5288. https://doi.org/10.5194/hess-18-5271-2014

Penna, D., Hopp, L., Scandellari, F., Allen, S. T., Benettin, P., Beyer, M., et al. (2018). Ideas and perspectives: Tracing terrestrial ecosystem water fluxes using hydrogen and oxygen stable isotopes—Challenges and opportunities from an interdisciplinary perspective. *Biogeosciences*, *15*(21), 6399–6415. https://doi.org/10.5194/bg-15-6399-2018

Penna, D., van Meerveld, H., Zuecco, G., Dalla Fontana, G., & Borga, M. (2016). Hydrological response of an alpine catchment to rainfall and snowmelt events. *Journal of Hydrology*, *537*, 382–397. https://doi.org/10.1016/j.jhydrol.2016.03.040

Penna, D., & van Meerveld, H. J. I. (2019). Spatial variability in the isotopic composition of water in small catchments and its effect on hydrograph separation. *WIREs Water*, *6*(5), e1367. https://doi.org/10.1002/wat2.1367

Perga, M.-E., Minaudo, C., Doda, T., Arthaud, F., Beria, H., Chmiel, H. E., et al. (2023). Near-bed stratification controls bottom hypoxia in ice-covered alpine lakes. *Limnology & Oceanography*, *68*(6), 1232–1246. https://doi.org/10.1002/lno.12341

Petersen, J., Deschamps, P., Hamelin, B., Fourré, E., Gonçalvès, J., Zouari, K., et al. (2018). Groundwater flowpaths and residence times inferred by ^{14}C, ^{36}Cl, and ^{4}He isotopes in the Continental Intercalaire aquifer (North-Western Africa). *Journal of Hydrology*, *560*, 11–23. https://doi.org/10.1016/j.jhydrol.2018.03.003

Pierchala, A., Rozanski, K., Dulinski, M., & Gorczyca, Z. (2022). Triple-isotope mass balance of mid-latitude, groundwater controlled lake. *Science of the Total Environment*, *814*, 151935. https://doi.org/10.1016/j.scitotenv.2021.151935

Pinder, G. F., & Jones, J. F. (1969). Determination of the ground-water component of peak discharge from the chemistry of total runoff. *Water Resources Research*, *5*(2), 438–445. https://doi.org/10.1029/wr005i002p00438

Pinos, J., Flury, M., Latron, J., & Llorens, P. (2023). Routing stemflow water through the soil via preferential flow: A dual-labelling approach with artificial tracers. *Hydrology and Earth System Sciences*, *27*(15), 2865–2881. https://doi.org/10.5194/hess-27-2865-2023

Popp, A. L., Beria, H., Sprenger, M., Ala-Aho, P., Coenders-Gerrits, M., Groh, J., et al. (2025). Supporting Information accompanying Table 1 of Popp, Beria et al., Recent advances in tracer-aided mixing modeling of water in the Critical Zone, Reviews of Geophysics [Dataset]. In *Reviews of Geophysics*. Zenodo. https://doi.org/10.5281/ZENODO.15440912

Popp, A. L., Manning, C. C., & Knapp, J. L. (2021). Rapid advances in mobile mass spectrometry enhance tracer hydrology and water management. *Water Resources Research*, *57*(6), e2021WR029890. https://doi.org/10.1029/2021WR029890

Popp, A. L., Pardo-Alvarez, A., Schilling, O., Musy, S., Peel, M., Purtschert, R., et al. (2021). A framework for untangling transient groundwater mixing and travel times. *Water Resources Research*, *57*(4), e2020WR028362. https://doi.org/10.1029/2020WR028362

Popp, A. L., Scheidegger, A., Moeck, C., Brennwald, M. S., & Kipfer, R. (2019). Integrating Bayesian groundwater mixing modeling with on-site helium analysis to identify unknown water sources. *Water Resources Research*, *55*(12), 10602–10615. https://doi.org/10.1029/2019WR025677

Poulain, A., Vincent, M., Gillon, M., Mayer, A., Anne-Laure, C.-P., Roland, S., et al. (2021). Enhanced pumping test using physicochemical tracers to determine surface-water/groundwater interactions in an alluvial island aquifer, river Rhône, France. *Hydrogeology Journal*, *29*(4), 1569–1585.

Pu, T., Qin, D., Kang, S., Niu, H., He, Y., & Wang, S. (2017). Water isotopes and hydrograph separation in different glacial catchments in the southeast margin of the Tibetan Plateau. *Hydrological Processes*, *31*(22), 3810–3826. https://doi.org/10.1002/hyp.11293

Pu, T., Wang, K., Kong, Y., Shi, X., Kang, S., Huang, Y., et al. (2020). Observing and modeling the isotopic evolution of snow meltwater on the Southeastern Tibetan Plateau. *Water Resources Research*, *56*(9), e2019WR026423. https://doi.org/10.1029/2019wr026423

Putman, A. L., Fiorella, R. P., Bowen, G. J., & Cai, Z. (2019). A global perspective on local meteoric water lines: Meta-analytic insight into fundamental controls and practical constraints. *Water Resources Research*, *55*(8), 6896–6910. https://doi.org/10.1029/2019wr025181

Radolinski, J., Pangle, L., Klaus, J., & Stewart, R. D. (2021). Testing the "two water worlds" hypothesis under variable preferential flow conditions. *Hydrological Processes*, *35*(6), e14252. https://doi.org/10.1002/hyp.14252

Rai, S. P., Singh, D., Jacob, N., Rawat, Y., Arora, M., & BhishmKumar. (2019). Identifying contribution of snowmelt and glacier melt to the Bhagirathi River (Upper Ganga) near snout of the Gangotri Glacier using environmental isotopes. *Catena*, *173*, 339–351. https://doi.org/10.1016/j.catena.2018.10.031

Ramírez, S. B., van Meerveld, I., & Seibert, J. (2023). Citizen science approaches for water quality measurements. *Science of the Total Environment*, *897*, 165436. https://doi.org/10.1016/j.scitotenv.2023.165436

Richards, L. A., Magnone, D., Boyce, A. J., Casanueva-Marenco, M. J., van Dongen, B. E., Ballentine, C. J., & Polya, D. A. (2018). Delineating sources of groundwater recharge in an arsenic-affected Holocene aquifer in Cambodia using stable isotope-based mixing models. *Journal of Hydrology*, *557*, 321–334. https://doi.org/10.1016/j.jhydrol.2017.12.012

Ritter, F., Berkelhammer, M., & Beysens, D. (2019). Dew frequency across the US from a network of in situ radiometers. *Hydrology and Earth System Sciences*, *23*(2), 1179–1197. https://doi.org/10.5194/hess-23-1179-2019

Rodhe, A. (1981). Spring flood meltwater or groundwater? Paper presented at the Nordic Hydrological Conference (Vemdalen, Sweden, August, 1980). *Hydrology Research*, *12*(1), 21–30. https://doi.org/10.2166/nh.1981.0002

Rosenberry, D. O., Lewandowski, J., Meinikmann, K., & Nützmann, G. (2015). Groundwater—The disregarded component in lake water and nutrient budgets. Part 1: Effects of groundwater on hydrology. *Hydrological Processes*, *29*(13), 2895–2921. https://doi.org/10.1002/hyp.10403

Ross, K. A., Gashugi, E., Gafasi, A., Wüest, A., & Schmid, M. (2015). Characterisation of the Subaquatic Groundwater Discharge That Maintains the Permanent Stratification within Lake Kivu; East Africa. *PLoS One*, *10*(3), e0121217. https://doi.org/10.1371/journal.pone.0121217

Rothfuss, Y., & Javaux, M. (2017). Reviews and syntheses: Isotopic approaches to quantify root water uptake: A review and comparison of methods. *Biogeosciences*, *14*(8), 2199–2224. https://doi.org/10.5194/bg-14-2199-2017

Rozanski, K., Froehlich, K., & Mook, W. G. (2001). *Environmental isotopes in the hydrological cycle: Principles and applications, v. III: Surface water*. UNESCO: United Nations Educational, Scientific and Cultural Organisation. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000124619

Rücker, A., Boss, S., Kirchner, J. W., & von Freyberg, J. (2019). Monitoring snowpack outflow volumes and their isotopic composition to better understand streamflow generation during rain-on-snow events. *Hydrology and Earth System Sciences*, *23*(7), 2983–3005. https://doi.org/10.5194/hess-23-2983-2019

Runyan, C., Wang, L., Lawrence, D., & D'Odorico, P. (2019). Ecohydrological controls on the deposition of non-rainfall water, N, and P to dryland ecosystems. In *Dryland ecohydrology* (pp. 121–137). Springer International Publishing. https://doi.org/10.1007/978-3-030-23269-6_6

Saaltink, M. W., Kohfahl, C., & Molano-Leno, L. (2020). Analysis of water vapor adsorption in soils by means of a lysimeter and numerical modeling. *Vadose Zone Journal*, *19*(1), e20012. https://doi.org/10.1002/vzj2.20012

Sachs, J. D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., & Rockström, J. (2019). Six Transformations to achieve the Sustainable Development Goals. *Nature Sustainability*, *2*(9), 805–814. https://doi.org/10.1038/s41893-019-0352-9

Sahraei, A., Houska, T., & Breuer, L. (2021). Deep learning for isotope hydrology: The application of long short-term memory to estimate high temporal resolution of the stable isotope concentrations in stream and groundwater. *Frontiers in Water*, *3*, 740044. https://doi.org/10.3389/frwa.2021.740044

Santoni, S., Garel, E., Gillon, M., Marc, V., Miller, J., Babic, M., et al. (2021). Assessing the hydrogeological resilience of a groundwater-dependent Mediterranean peatland: Impact of global change and role of water management strategies. *Science of the Total Environment*, *768*, 144721. https://doi.org/10.1016/j.scitotenv.2020.144721

Sanz, D., Valiente, N., Dountcheva, I., Muñoz-Martín, A., Cassiraga, E., & Gómez-Alday, J. J. (2022). Geometry of the modelled freshwater/salt-water interface under variable-density-driven flow (Pétrola Lake, SE Spain). *Hydrogeology Journal*, *30*(3), 975–988. https://doi.org/10.1007/s10040-022-02456-x

Schilling, O. S., Parajuli, A., Tremblay Otis, C., Müller, T., Antolinez Quijano, W., Tremblay, Y., et al. (2021). Quantifying groundwater recharge dynamics and unsaturated zone processes in snow-dominated catchments via on-site dissolved gas analysis. *Water Resources Research*, *57*(2), e2020WR028479. https://doi.org/10.1029/2020WR028479

Schmieder, J., Garvelmann, J., Marke, T., & Strasser, U. (2018). Spatio-temporal tracer variability in the glacier melt end-member—How does it affect hydrograph separation results? *Hydrological Processes*, *32*(12), 1828–1843. https://doi.org/10.1002/hyp.11628

Schmieder, J., Seeger, S., Weiler, M., & Strasser, U. (2019). "Teflon Basin" or Not? A high-elevation catchment transit time modeling approach. *Hydrology*, *6*(4), 92. https://doi.org/10.3390/hydrology6040092

Schneider, A., Borsdorff, T., aan de Brugh, J., Lorente, A., Aemisegger, F., Noone, D., et al. (2022). Retrieving H_2O/HDO columns over cloudy and clear-sky scenes from the tropospheric monitoring instrument (TROPOMI). *Atmospheric Measurement Techniques*, *15*(7), 2251–2275. https://doi.org/10.5194/amt-15-2251-2022

Shaw, S. B., Marrs, J., Bhattarai, N., & Quackenbush, L. (2014). Longitudinal study of the impacts of land cover change on hydrologic response in four mesoscale watersheds in New York State, USA. *Journal of Hydrology*, *519*, 12–22. https://doi.org/10.1016/j.jhydrol.2014.06.055

Shen, C., Appling, A. P., Gentine, P., Bandai, T., Gupta, H., Tartakovsky, A., et al. (2023). Differentiable modelling to unify machine learning and physical models for geosciences. *Nature Reviews Earth & Environment*, *4*(8), 552–567. https://doi.org/10.1038/s43017-023-00450-9

Sklash, M. G., & Farvolden, R. N. (1979). The role of groundwater in storm runoff. *Journal of Hydrology*, *43*(1–4), 45–65. https://doi.org/10.1016/0022-1694(79)90164-1

Sklash, M. G., Farvolden, R. N., & Fritz, P. (1976). A conceptual model of watershed response to rainfall, developed through the use of oxygen-18 as a natural tracer. *Canadian Journal of Earth Sciences*, *13*(2), 271–283. https://doi.org/10.1139/e76-029

Smith, D. F., Moore, M. T., Anderson, R. L., & Carey, A. E. (2021). Hydrological separation of event and pre-event soil water in a cultivated landscape. *ACS Agricultural Science & Technology*, *2*(1), 32–41. https://doi.org/10.1021/acsagscitech.1c00088

Snyder, K. A., Morrow, A. C., Stringham, T. K., & Allen, S. T. (2024). Do trees use stemflow water? A manipulative experiment on Singleleaf piñon and Utah juniper in Great Basin woodlands. *Tree Physiology*, *44*(12), tpae143. https://doi.org/10.1093/treephys/tpae143

Soulsby, C., Petry, J., Brewer, M., Dunn, S., Ott, B., & Malcolm, I. (2003). Identifying and assessing uncertainty in hydrological pathways: A novel approach to end member mixing in a Scottish agricultural catchment. *Journal of Hydrology*, *274*(1–4), 109–128. https://doi.org/10.1016/s0022-1694(02)00398-0

Sprenger, M., & Allen, S. T. (2020). What ecohydrologic separation is and where we can go with it. *Water Resources Research*, *56*(7), e2020WR027238. https://doi.org/10.1029/2020WR027238

Sprenger, M., Carroll, R. W. H., Dennedy-frank, J., Siirila-woodburn, E. R., Newcomer, M. E., Brown, W., et al. (2022). Variability of snow and rainfall partitioning into evapotranspiration and summer runoff across nine mountainous catchments. *Geophysical Research Letters*, *49*(13), e2022GL099324. https://doi.org/10.1029/2022GL099324

Sprenger, M., Carroll, R. W. H., Marchetti, D., Bern, C., Beria, H., Brown, W., et al. (2024). Stream water sourcing from high-elevation snowpack inferred from stable isotopes of water: A novel application of d-excess values. *Hydrology and Earth System Sciences*, *28*(7), 1711–1723. https://doi.org/10.5194/hess-28-1711-2024

Sprenger, M., Leistert, H., Gimbel, K., & Weiler, M. (2016). Illuminating hydrological processes at the soil-vegetation-atmosphere interface with water stable isotopes. *Reviews of Geophysics*, *54*(3), 674–704. https://doi.org/10.1002/2015rg000515

Sprenger, M., Llorens, P., Cayuela, C., Gallart, F., & Latron, J. (2019). Mechanisms of consistently disjunct soil water pools over (pore) space and time. *Hydrology and Earth System Sciences*, *23*(6), 2751–2762. https://doi.org/10.5194/hess-23-2751-2019

Sprenger, M., Tetzlaff, D., & Soulsby, C. (2017). Soil water stable isotopes reveal evaporation dynamics at the soil–plant–atmosphere interface of the critical zone. *Hydrology and Earth System Sciences*, *21*(7), 3839–3858. https://doi.org/10.5194/hess-21-3839-2017

Stadnyk, T. A., Delavau, C., Kouwen, N., & Edwards, T. W. D. (2013). Towards hydrological model calibration and validation: Simulation of stable water isotopes using the isoWATFLOOD model. *Hydrological Processes*, *27*(25), 3791–3810. https://doi.org/10.1002/hyp.9695

Stadnyk, T. A., & Holmes, T. L. (2020). On the value of isotope-enabled hydrological model calibration. *Hydrological Sciences Journal*, *65*(9), 1–14. https://doi.org/10.1080/02626667.2020.1751847

Stadnyk, T. A., & Holmes, T. L. (2023). Large scale hydrologic and tracer aided modelling: A review. *Journal of Hydrology*, *618*, 129177. https://doi.org/10.1016/J.JHYDROL.2023.129177

Stock, B. C., Jackson, A. L., Ward, E. J., Parnell, A. C., Phillips, D. L., & Semmens, B. X. (2018). Analyzing mixing systems using a new generation of Bayesian tracer mixing models. *PeerJ*, *2018*(6), 1–27. https://doi.org/10.7717/peerj.5096

Stumpp, C., Klaus, J., & Stichler, W. (2014). Analysis of long-term stable isotopic composition in German precipitation. *Journal of Hydrology*, *517*, 351–361. https://doi.org/10.1016/j.jhydrol.2014.05.034

Sutanto, S. J., Wenninger, J., Coenders-Gerrits, A. M. J., & Uhlenbrook, S. (2012). Partitioning of evaporation into transpiration, soil evaporation and interception: A comparison between isotope measurements and a HYDRUS-1D model. *Hydrology and Earth System Sciences*, *16*(8), 2605–2616. https://doi.org/10.5194/hess-16-2605-2012

Taylor, S., Feng, X., Kirchner, J. W., Osterhuber, R., Klaue, B., & Renshaw, C. E. (2001). Isotopic evolution of a seasonal snowpack and its melt. *Water Resources Research*, *37*(3), 759–769. https://doi.org/10.1029/2000wr900341

Tetzlaff, D., Buttle, J., Carey, S. K., McGuire, K., Laudon, H., & Soulsby, C. (2015). Tracer-based assessment of flow paths, storage and runoff generation in northern catchments: A review. *Hydrological Processes*, *29*(16), 3475–3490. https://doi.org/10.1002/hyp.10412

Thaw, M., Visser, A., Bibby, R., Deinhart, A., Oerter, E., & Conklin, M. (2021). Vegetation water sources in California's Sierra Nevada (USA) are young and change over time, a multi-isotope ($\Delta^{18}O$, $\Delta^{2}H$, ^{3}H) tracer approach. *Hydrological Processes*, *35*(6), e14249. https://doi.org/10.1002/hyp.14249

Thiros, N. E., Siirila-Woodburn, E. R., Dennedy-Frank, P. J., Williams, K. H., & Gardner, W. P. (2023). Constraining bedrock groundwater residence times in a mountain system with environmental tracer observations and bayesian uncertainty quantification. *Water Resources Research*, *59*(2), e2022WR033282. https://doi.org/10.1029/2022wr033282

Tian, C., Jiao, W., Beysens, D., Farai Kaseke, K., Medici, M.-G., Li, F., & Wang, L. (2021). Investigating the role of evaporation in dew formation under different climates using ^{17}O-excess. *Journal of Hydrology*, *592*, 125847. https://doi.org/10.1016/j.jhydrol.2020.125847

Uclés, O., Villagarcía, L., Cantón, Y., Lázaro, R., & Domingo, F. (2015). Non-rainfall water inputs are controlled by aspect in a semiarid ecosystem. *Journal of Arid Environments*, *113*, 43–50. https://doi.org/10.1016/j.jaridenv.2014.09.009

Uhlenbrook, S., Frey, M., Leibundgut, C., & Maloszewski, P. (2002). Hydrograph separations in a mesoscale mountainous basin at event and seasonal timescales. *Water Resources Research*, *38*(6). https://doi.org/10.1029/2001wr000938

Uhlenbrook, S., & Hoeg, S. (2003). Quantifying uncertainties in tracer-based hydrograph separations: A case study for two-three- and five-component hydrograph separations in a mountainous catchment. *Hydrological Processes*, *17*(2), 431–453. https://doi.org/10.1002/hyp.1134

Valiente, N., Carrey, R., Otero, N., Soler, A., Sanz, D., Muñoz-Martín, A., et al. (2018). A multi-isotopic approach to investigate the influence of land use on nitrate removal in a highly saline lake-aquifer system. *Science of the Total Environment*, *631–632*, 649–659. https://doi.org/10.1016/j.scitotenv.2018.03.059

Valiente, N., Eiler, A., Allesson, L., Andersen, T., Clayer, F., Crapart, C., et al. (2022). Catchment properties as predictors of greenhouse gas concentrations across a gradient of boreal lakes. *Frontiers in Environmental Science*, *1668*, 880619. https://doi.org/10.3389/fenvs.2022.880619

Valiente, N., Gil-Márquez, J. M., Gómez-Alday, J. J., & Andreo, B. (2020). Unraveling groundwater functioning and nitrate attenuation in evaporitic karst systems from southern Spain: An isotopic approach. *Applied Geochemistry*, *123*, 104820. https://doi.org/10.1016/j.apgeochem.2020.104820

Valois, R., Araya Vargas, J., MacDonell, S., Guzman Pinones, C., Fernandoy, F., Yanez Carrizo, G., et al. (2021). Improving the underground structural characterization and hydrological functioning of an Andean peatland using geoelectrics and water stable isotopes in semi-arid Chile. *Environmental Earth Sciences*, *80*(1), 41. https://doi.org/10.1007/s12665-020-09331-6

Van Stan, J. T., & Allen, S. T. (2020). What We Know About Stemflow's Infiltration Area. *Frontiers in Forests and Global Change*, *3*, 61. https://doi.org/10.3389/ffgc.2020.00061

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

Voigt, C., Herwartz, D., Dorador, C., & Staubwasser, M. (2021). Triple oxygen isotope systematics of evaporation and mixing processes in a dynamic desert lake system. *Hydrology and Earth System Sciences*, *25*(3), 1211–1228. https://doi.org/10.5194/hess-25-1211-2021

Volkmann, T. H. M., Haberer, K., Gessler, A., & Weiler, M. (2016). High-resolution isotope measurements resolve rapid ecohydrological dynamics at the soil–plant interface. *New Phytologist*, *210*(3), 839–849. https://doi.org/10.1111/nph.13868

von Freyberg, J., Bjarnadóttir, T. R., & Allen, S. T. (2019). Influences of forest canopy on snowpack accumulation and isotope ratios. *Hydrological Processes*, *34*(3), 679–690. https://doi.org/10.1002/hyp.13617

von Freyberg, J., Knapp, J. L. A., Rücker, A., Studer, B., & Kirchner, J. W. (2020). Technical note: Evaluation of a low-cost evaporation protection method for portable water samplers. *Hydrology and Earth System Sciences*, *24*(12), 5821–5834. https://doi.org/10.5194/hess-24-5821-2020

von Freyberg, J., Studer, B., & Kirchner, J. W. (2017). A lab in the field: High-frequency analysis of water quality and stable isotopes in stream water and precipitation. *Hydrology and Earth System Sciences*, *21*(3), 1721–1739. https://doi.org/10.5194/hess-21-1721-2017

Vreča, P., Pavšek, A., & Kocman, D. (2022). SLONIP—A Slovenian Web-Based Interactive Research Platform on Water Isotopes in Precipitation. *Water*, *14*(13), 2127. https://doi.org/10.3390/w14132127

Wang, L., Caylor, K. K., Villegas, J. C., Barron-Gafford, G. A., Breshears, D. D., & Huxman, T. E. (2010). Partitioning evapotranspiration across gradients of woody plant cover: Assessment of a stable isotope technique. *Geophysical Research Letters*, *37*(9). https://doi.org/10.1029/2010gl043228

Wang, S., Gao, Y., Jia, J., Lu, Y., Sun, K., Ha, X., et al. (2022). Vertically stratified water source characteristics and associated driving mechanisms of particulate organic carbon in a large floodplain lake system. *Water Research*, *209*, 117963. https://doi.org/10.1016/j.watres.2021.117963

Welch, C., Smith, A. A., & Stadnyk, T. A. (2017). Linking physiography and evaporation using the isotopic composition of river water in 16 Canadian boreal catchments. *Hydrological Processes*, *32*(2), 170–184. https://doi.org/10.1002/hyp.11396

Wen, X.-F., Lee, X., Sun, X.-M., Wang, J.-L., Hu, Z.-M., Li, S.-G., & Yu, G.-R. (2012). Dew water isotopic ratios and their relationships to ecosystem water pools and fluxes in a cropland and a grassland in China. *Oecologia*, *168*(2), 549–561. https://doi.org/10.1007/s00442-011-2091-0

Williams, M. R., Ford, W. I., & Mumbi, R. C. K. (2023). Preferential flow in the shallow vadose zone: Effect of rainfall intensity, soil moisture, connectivity, and agricultural management. *Hydrological Processes*, *37*(12), e15057. https://doi.org/10.1002/hyp.15057

Winograd, I. J., Riggs, A. C., & Coplen, T. B. (1998). The relative contributions of summer and cool-season precipitation to groundwater recharge, Spring Mountains, Nevada, USA. *Hydrogeology Journal*, *6*(1), 77–93. https://doi.org/10.1007/s100400050135

Winter, T. C., Harvey, J. W., Franke, O. L., & Alley, W. M. (1998). *Ground water and surface water: A single resource*. U.S. Geological Survey. https://doi.org/10.3133/cir1139

Xia, C., Liu, G., & Luo, J. (2023). Stable isotopes reveal the effect of canopy and litter layer interception on water recharge in a subtropical Manmade Forest of Southwest China. *Forests*, *14*(1), 129. https://doi.org/10.3390/f14010129

Xu, X., Guan, H., Skrzypek, G., & Simmons, C. T. (2019). Root-zone moisture replenishment in a native vegetated catchment under Mediterranean climate. *Hydrological Processes*, *33*(18), 2394–2407. https://doi.org/10.1002/hyp.13475

Xu Fei, E., & Harman, C. J. (2022). A data-driven method for estimating the composition of end-members from stream water chemistry time series. *Hydrology and Earth System Sciences*, *26*(8), 1977–1991. https://doi.org/10.5194/hess-26-1977-2022

Zajíček, A., Pomije, T., & Kvítek, T. (2016). Event water detection in tile drainage runoff using stable isotopes and a water temperature in small agricultural catchment in Bohemian-Moravian Highlands, Czech Republic. *Environmental Earth Sciences*, *75*(9), 838. https://doi.org/10.1007/s12665-016-5561-1
Zhao, L., Liu, X., Wang, N., Kong, Y., Song, Y., He, Z., et al. (2019). Contribution of recycled moisture to local precipitation in the inland Heihe River Basin. *Agricultural and Forest Meteorology*, *271*, 316–335. https://doi.org/10.1016/j.agrformet.2019.03.014
Zhi, W., Appling, A. P., Golden, H. E., Podgorski, J., & Li, L. (2024). Deep learning for water quality. *Nature Water*, *2*(3), 228–241. https://doi.org/10.1038/s44221-024-00202-z
Zhuang, Y., Zhao, W., Luo, L., & Wang, L. (2021). Dew formation characteristics in the gravel desert ecosystem and its ecological roles on Reaumuria soongorica. *Journal of Hydrology*, *603*, 126932. https://doi.org/10.1016/j.jhydrol.2021.126932
Zongxing, L., Qi, F., Wei, L., Tingting, W., Xiaoyan, G., Zongjie, L., et al. (2015). The stable isotope evolution in Shiyi glacier system during the ablation period in the north of Tibetan Plateau, China. *Quaternary International*, *380*, 262–271. https://doi.org/10.1016/j.quaint.2015.02.013
Zuecco, G., Carturan, L., De Blasi, F., Seppi, R., Zanoner, T., Penna, D., et al. (2019). Understanding hydrological processes in glacierized catchments: Evidence and implications of highly variable isotopic and electrical conductivity data. *Hydrological Processes*, *33*(5), 816–832. https://doi.org/10.1002/hyp.13366
Zuecco, G., Marchina, C., Censini, M., Todini-Zicavo, D., Cassiani, G., & Borga, M. (2025). A simple experiment to trace stemflow infiltration: Advantages and challenges of using stable isotopes of hydrogen and oxygen and electrical resistivity tomography. *Vadose Zone Journal*, *24*(1), e20397. https://doi.org/10.1002/vzj2.20397

References From the Supporting Information

Allen, S. T., & Kirchner, J. W. (2022). Potential effects of cryogenic extraction biases on plant water source partitioning inferred from xylem-water isotope ratios. *Hydrological Processes*, *36*(2), e14483. https://doi.org/10.1002/hyp.14483
Allen, S. T., Sprenger, M., Bowen, G., & Brooks, R. (2022). Chapter 18: Spatial and temporal variations in plant source water: O and H isotope ratios from precipitation to xylem water. *Stable Isotopes in Tree Rings*, *8*.
Barbeta, A., Burlett, R., Martín-Gómez, P., Fréjaville, B., Devert, N., Wingate, L., et al. (2022). Evidence for distinct isotopic compositions of sap and tissue water in tree stems: Consequences for plant water source identification. *New Phytologist*, *233*(3), 1121–1132. https://doi.org/10.1111/nph.17857
Benettin, P., Nehemy, M. F., Cernusak, L. A., Kahmen, A., & McDonnell, J. J. (2021). On the use of leaf water to determine plant water source: A proof of concept. *Hydrological Processes*, *35*(3), e14073. https://doi.org/10.1002/hyp.14073
Beyer, M., Kühnhammer, K., & Dubbert, M. (2020). In situ measurements of soil and plant water isotopes: A review of approaches, practical considerations and a vision for the future. *Hydrology and Earth System Sciences*, *24*(9), 4413–4440. https://doi.org/10.5194/hess-24-4413-2020
Cernusak, L. A., Barbour, M. M., Arndt, S. K., Cheesman, A. W., English, N. B., Feild, T. S., et al. (2016). Stable isotopes in leaf water of terrestrial plants. *Plant, Cell and Environment*, *39*(5), 1087–1102. https://doi.org/10.1111/pce.12703
Corraide da Silva, L., Oliveira Filho, D., Acioli Imbuzeiro, H. M., & Barros Monteiro, P. M. (2021). Analysis of different condensing surfaces for dew harvesting. *Water Supply*, *22*(1), 697–706. https://doi.org/10.2166/ws.2021.242
Ehleringer, J. R., & Dawson, T. E. (1992). Water uptake by plants: Perspectives from stable isotope composition. *Plant, Cell and Environment*, *15*(9), 1073–1082. https://doi.org/10.1111/j.1365-3040.1992.tb01657.x
Geißler, K., Heblack, J., Uugulu, S., Wanke, H., & Blaum, N. (2019). Partitioning of water between differently sized shrubs and potential groundwater recharge in a Semiarid Savanna in Namibia. *Frontiers in Plant Science*, *10*, 1411. https://doi.org/10.3389/fpls.2019.01411
Gerlein-Safdi, C., Gauthier, P. P., & Caylor, K. K. (2018). Dew-induced transpiration suppression impacts the water and isotope balances of colocasia leaves. *Oecologia*, *187*(4), 1041–1051. https://doi.org/10.1007/s00442-018-4199-y
Giraud, M., Groh, J., Gerke, H., Brüggemann, N., Vereecken, H., & Pütz, T. (2021). Soil nitrogen dynamics in a managed temperate grassland under changed climatic conditions. *Water*, *13*(7), 931. https://doi.org/10.3390/w13070931
Giuditta, E., Coenders-Gerrits, A., Bogaard, T., Wenninger, J., Greco, R., & Rutigliano, F. (2018). Measuring changes in forest floor evaporation after prescribed burning in southern Italy Pine plantations. *Agricultural and Forest Meteorology*, *256–257*, 516–525. https://doi.org/10.1016/j.agrformet.2018.04.004
Gröning, M., Lutz, H., Roller-Lutz, Z., Kralik, M., Gourcy, L., & Pöltenstein, L. (2012). A simple rain collector preventing water re-evaporation dedicated for $\Delta^{18}O$ and $\Delta^{2}H$ analysis of cumulative precipitation samples. *Journal of Hydrology*, *448–449*, 195–200. https://doi.org/10.1016/j.jhydrol.2012.04.041
IAEA. (2007). *Introduction to water sampling and analysis for isotope hydrology*. International Atomic Energy Agency. Vienna Retrieved from https://www.iaea.org/publications/7716/introduction-to-water-sampling-and-analysis-for-isotope-hydrology
Keeling, C. D. (1961). The concentration and isotopic abundances of carbon dioxide in rural and marine air. *Geochimica et Cosmochimica Acta*, *24*(3–4), 277–298. https://doi.org/10.1016/0016-7037(61)90023-0
Klemm, O., & Wrzesinsky, T. (2007). Fog deposition fluxes of water and ions to a mountainous site in central Europe. *Tellus B: Chemical and Physical Meteorology*, *59*(4). https://doi.org/10.3402/tellusb.v59i4.17050
Magh, R.-K., Eiferle, C., Burzlaff, T., Dannenmann, M., Rennenberg, H., & Dubbert, M. (2020). Competition for water rather than facilitation in mixed beech-fir forests after drying-wetting cycle. *Journal of Hydrology*, *587*, 124944. https://doi.org/10.1016/j.jhydrol.2020.124944
Mattei, A., Barbecot, F., Guillon, S., Goblet, P., Hélie, J., & Meyzonnat, G. (2019). Improved accuracy and precision of water stable isotope measurements using the direct vapour equilibration method. *Rapid Communications in Mass Spectrometry*, *33*(20), 1613–1622. https://doi.org/10.1002/rcm.8494
Michelsen, N., van Geldern, R., Roßmann, Y., Bauer, I., Schulz, S., Barth, J. A., & Schüth, C. (2018). Comparison of precipitation collectors used in isotope hydrology. *Chemical Geology*, *488*, 171–179. https://doi.org/10.1016/j.chemgeo.2018.04.032
Millar, C., Janzen, K., Nehemy, M. F., Koehler, G., Hervé-Fernández, P., Wang, H., et al. (2022). On the urgent need for standardization in isotope-based ecohydrological investigations. *Hydrological Processes*, *36*(10), e14698. https://doi.org/10.1002/hyp.14698
Muselli, M., Beysens, D., Mileta, M., & Milimouk, I. (2009). Dew and rain water collection in the Dalmatian Coast, Croatia. *Atmospheric Research*, *92*(4), 455–463. https://doi.org/10.1016/j.atmosres.2009.01.004
Natali, S., Nigro, M., Baneschi, I., Giannecchini, R., Doveri, M., & Zanchetta, G. (2024). On the reliability of tube-dip-in-water precipitation collectors in isotope hydrology: A field experiment for low rainfall amounts. *Journal of Hydrology*, *644*, 132096. https://doi.org/10.1016/j.jhydrol.2024.132096

Orlowski, N., Frede, H.-G., Brüggemann, N., & Breuer, L. (2013). Validation and application of a cryogenic vacuum extraction system for soil and plant water extraction for isotope analysis. *Journal of Sensors and Sensor Systems*, *2*(2), 179–193. https://doi.org/10.5194/jsss-2-179-2013

Penna, D., Zanotelli, D., Scandellari, F., Aguzzoni, A., Engel, M., Tagliavini, M., & Comiti, F. (2021). Water uptake of apple trees in the Alps: Where does irrigation water go? *Ecohydrology*, *14*(6), e2306. https://doi.org/10.1002/eco.2306

Peters, L. I., & Yakir, D. (2008). A direct and rapid leaf water extraction method for isotopic analysis. *Rapid Communications in Mass Spectrometry*, *22*(18), 2929–2936. https://doi.org/10.1002/rcm.3692

Quade, M., Brüggemann, N., Graf, A., Vanderborght, J., Vereecken, H., & Rothfuss, Y. (2018). Investigation of kinetic isotopic fractionation of water during bare soil evaporation. *Water Resources Research*, *54*(9), 6909–6928. https://doi.org/10.1029/2018wr023159

Rothfuss, Y., Quade, M., Brüggemann, N., Graf, A., Vereecken, H., & Dubbert, M. (2021). Reviews and syntheses: Gaining insights into evapotranspiration partitioning with novel isotopic monitoring methods. *Biogeosciences*, *18*(12), 3701–3732. https://doi.org/10.5194/bg-18-3701-2021

Seeger, S., & Weiler, M. (2021). Temporal dynamics of tree xylem water isotopes: In situ monitoring and modeling. *Biogeosciences*, *18*(15), 4603–4627. https://doi.org/10.5194/bg-18-4603-2021

Siegwolf, R. T. W., Brooks, R. J., Roden, J., & Sauer, M. (2022). Stable Isotopes in Tree Rings. In *Inferring Physiological, Climatic and Environmental Responses* (Vol. 3). https://doi.org/10.1007/978-3-030-92698-4

Singh, G., Kaur, G., Williard, K., Schoonover, J., & Kang, J. (2017). Monitoring of water and solute transport in the vadose zone: A review. *Vadose Zone Journal*, *17*(1), 1–23. https://doi.org/10.2136/vzj2016.07.0058

Sánchez-Murillo, R., Todini-Zicavo, D., Poca, M., Birkel, C., Esquivel-Hernández, G., Chavarría, M. M., et al. (2023). Dry season plant water sourcing in contrasting tropical ecosystems of Costa Rica. *Ecohydrology*, *16*(5), e2541. https://doi.org/10.1002/eco.2541

Sprenger, M., Herbstritt, B., & Weiler, M. (2015). Established methods and new opportunities for pore water stable isotope analysis. *Hydrological Processes*, *29*(25), 5174–5192. https://doi.org/10.1002/hyp.10643

Sprenger, M., Stumpp, C., Weiler, M., Aeschbach, W., Allen, S. T., Benettin, P., et al. (2019). The demographics of water: A review of water ages in the critical zone. *Reviews of Geophysics*, *57*(3), 800–834. https://doi.org/10.1029/2018RG000633

Sträter, E., Westbeld, A., & Klemm, O. (2010). Pollution in coastal fog at Alto Patache, Northern Chile. *Environmental Science and Pollution Research*, *17*(9), 1563–1573. https://doi.org/10.1007/s11356-010-0343-x

Vreča, P., & Malenšek, N. (2016). Slovenian network of isotopes in precipitation (SLONIP)-a review of activities in the period 1981–2015. *Geologija*, *59*(1), 67–83. https://doi.org/10.5474/geologija.2016.004

Volkmann, T. H. M., & Weiler, M. (2014). Continual in situ monitoring of pore water stable isotopes in the subsurface. *Hydrology and Earth System Sciences*, *18*(5), 1819–1833. https://doi.org/10.5194/hess-18-1819-2014

Wahl, S., Steen-Larsen, H. C., Reuder, J., & Hörhold, M. (2021). Quantifying the stable water isotopologue exchange between the snow surface and lower atmosphere by direct flux measurements. *Journal of Geophysical Research: Atmospheres*, *126*(13), e2020JD034400. https://doi.org/10.1029/2020jd034400

Wassenaar, L., Hendry, M., Chostner, V., & Lis, G. (2008). High resolution pore water water δ^2H and δ^{18}O measurements by $H_2O_{(liquid)}$—$H_2O_{(vapor)}$ equilibration laser spectroscopy. *Environmental Science & Technology*, *42*(24), 9262–9267. https://doi.org/10.1021/es802065s

Weihermüller, L., Siemens, J., Deurer, M., Knoblauch, S., Rupp, H., Göttlein, A., & Pütz, T. (2007). In situ soil water extraction: A review. *Journal of Environmental Quality*, *36*(6), 1735–1748. https://doi.org/10.2134/jeq2007.0218

Wen, M., Zhao, X., Si, B., He, D., Li, M., Gao, X., et al. (2023). Inter-comparison of extraction methods for plant water isotope analysis and its indicative significance. *Journal of Hydrology*, *625*, 130015. https://doi.org/10.1016/j.jhydrol.2023.130015

West, A. G., Patrickson, S. J., & Ehleringer, J. R. (2006). Water extraction times for plant and soil materials used in stable isotope analysis. *Rapid Communications in Mass Spectrometry*, *20*(8), 1317–1321. https://doi.org/10.1002/rcm.2456

Yakir, D., & Sternberg, L. D. S. L. (2000). The use of stable isotopes to study ecosystem gas exchange. *Oecologia*, *123*(3), 297–311. https://doi.org/10.1007/s004420051016

Zuecco, G., Amin, A., Frentress, J., Engel, M., Marchina, C., Anfodillo, T., et al. (2022). A comparative study of plant water extraction methods for isotopic analyses: Scholander-type pressure chamber vs. cryogenic vacuum distillation. *Hydrology and Earth System Sciences*, *26*(13), 3673–3689. https://doi.org/10.5194/hess-26-3673-2022