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Using isotopes to understand landscape-scale connectivity in a groundwater-dominated, lowland catchment under drought conditions

Lukas Kleine[1,2] | Doerthe Tetzlaff[1,2,3] | Aaron Smith[1] |
Tobias Goldhammer[1] | Chris Soulsby[1,3,4]

[1]Leibniz Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany

[2]Department of Geography, Humboldt-Universität zu Berlin, Berlin, Germany

[3]Northern Rivers Institute, University of Aberdeen, St. Mary's Building, Kings College, Old Aberdeen, UK

[4]Chair of Water Resources Management and Modeling of Hydrosystems, Technical University Berlin, Berlin, Germany

Correspondence
Lukas Kleine, Humboldt-Universität zu Berlin and IGB Leibniz Institute of Freshwater Ecology and Inland Fisheries, Mueggelseedamm 310, 12587 Berlin, Germany.
Email: l.kleine@igb-berlin.de

Abstract

The Demnitzer Millcreek catchment (DMC), is a 66 km^2 long-term experimental catchment located 50 km SE of Berlin. Monitoring over the past 30 years has focused on hydrological and biogeochemical changes associated with de-intensification of farming and riparian restoration in the low-lying landscape dominated by rain-fed farming and forestry. However, the hydrological function of the catchment, which is closely linked to nutrient fluxes and highly sensitive to climatic variability, is still poorly understood. In the last 3 years, a prolonged drought period with below-average rainfall and above-average temperatures has resulted in marked hydrological change. This caused low soil moisture storage in the growing season, agricultural yield losses, reduced groundwater recharge, and intermittent streamflows in parts of an increasingly disconnected channel network. This paper focuses on a two-year long isotope study that sought to understand how different parts of the catchment affect ecohydrological partitioning, hydrological connectivity and streamflow generation during drought conditions. The work has shown the critical importance of groundwater storage in sustaining flows, basic in-stream ecosystem services and the dominant influence of vegetation on groundwater recharge. Recharge was much lower and occurred during a shorter window of time in winter under forests compared to grasslands. Conversely, groundwater recharge was locally enhanced by the restoration of riparian wetlands and storage-dependent water losses from the stream to the subsurface. The isotopic variability displayed complex emerging spatio-temporal patterns of stream connectivity and flow duration during droughts that may have implications for in-stream solute transport and future ecohydrological interactions between landscapes and riverscapes. Given climate projections for drier and warmer summers, reduced and increasingly intermittent streamflows are very likely not just in the study region, but in similar lowland areas across Europe. An integrated land

and water management strategy will be essential to sustaining catchment ecosystem services in such catchment systems in future.

1 | INTRODUCTION

Global climate change and population growth are increasing pressure on agricultural landscapes, threatening food and water security in many lowland catchments. This underlines the need for experimental observatories in such environments (Turral et al., 2011; Tetzlaff et al., 2017). An example for such pressures was the recent European drought of 2018 (continuing into 2020) where a prolonged period of warm and dry weather severely affected water availability over extensive areas, with a significant number of headwater streams ceasing to flow (Buras et al., 2020; Toreti et al., 2019). Water resources in the extensive, glacially formed, lowland landscape of the North German Plain (NGP) sustain food production (Barkmann et al., 2017; Gutzler et al., 2015) and water supplies to large cities like Berlin. In lowland catchments in the NGP, streams are often dominated by groundwater but it is still unclear how such catchments function hydrologically in both space (e.g., within a catchment) and time (Boulton & Hancock, 2006). Often, lowlands catchments are understudied in favour of landscapes with stronger topographic controls on drainage of surface and subsurface water (Devito et al., 2005). Thus, there is a weak evidence base for understanding how drought affects recharge and streamflows in such lowland areas, including the seasonal cessation of discharge (Germer et al., 2011). This is alarming, given climate change scenarios for the region which predict significantly drier and warmer summers (Mirshel et al., 2020) with a precipitation shift towards winter (Cubasch & Kadow, 2011).

To address this research gap, an ecohydrological study was initiated in the 66 km^2 Demnitzer Millcreek catchment (DMC), in the State of Brandenburg near Berlin (Figure 1) in 2018. This area is part of the NGP. A challenge of working in heavily managed agricultural catchments like DMC is assessing how a long legacy of constantly changing anthropogenic activities affects hydrological function, and how this is affected by non-stationary climatic conditions. In lowland catchments with extensive aquifers, understanding groundwater recharge and groundwater-surface water exchanges is a major research need (Kløve et al., 2014). Residual "blue" water fluxes, sustaining recharge and streamflow, are highly dependent on ecohydrological partitioning and the "green" water fluxes that return moisture back into the atmosphere. It is increasingly recognized how profoundly and subtly catchment hydrology is influenced by land use and vegetation cover (Dubbert & Werner, 2019). Elucidating the subsequent linkages between ecohydrological partitioning and hydrological connectivity at the catchment scale is crucial to understand groundwater recharge and runoff generation, as well as informing land and water management in lowland catchments.

The impact of droughts over the last decade have also highlighted the importance of intermittent streams – that is, streams which temporarily cease to flow at some point in time and space (Acuña et al., 2014). Such systems comprise half of the global river network (Datry et al., 2014) and their extent and distribution are increasing in many areas as a result of increasing human water withdrawal and climate change (Shumilova et al., 2019). A characteristic feature of the 2018 drought in the DMC (and similar lowland headwater streams) was the prolonged cessation of streamflow until well into the following winter (Smith, Tetzlaff, Gelbrecht, et al., 2020). Thus, the dynamic, seasonal interplay of temporary streamflow and bidirectional stream-groundwater interactions in headwater streams like the DMC highlights the importance of focal areas for groundwater recharge from streams (Zimmer & McGlynn, 2017a). Despite this, we still poorly understand how, why and where streams like the DMC expand, contract and interact with adjacent aquifers (Zimmer & McGlynn, 2017b). Any assessment of climate impacts on flow performance of groundwater dependent stream networks in anthropogenically influenced lowlands demand thorough understanding of the local hydrological system (van Engelenburg et al., 2018) and the structuring of the landscape (Bertrand et al., 2012) which can be highly place specific (Ward et al., 2020).

Gaining landscape scale understanding of groundwater-surface water interactions and hydrological connectivity requires the use of extensive instrumentation and integrating techniques that go beyond point scale hydrometric measurements. The factors for regional timing and spatial variability of surface water connectivity dynamics and groundwater-surface water interactions are not well constrained in most lowland areas (Lewandowski et al., 2009). In this regard, isotope ratios of oxygen and hydrogen have proven to be effective tools to trace fluxes in the terrestrial water cycle in an integrated way at large scales (Kendall & Mcdonnell, 2012; Penna et al., 2018). Naturally occurring isotopic variation in precipitation can be used as a basis for tracing water in the "critical zone" (the thin dynamic "life zone" of the terrestrial Earth, extending from the top of the vegetation canopy through the soils and down to fresh bedrock and the bottom of groundwater, Grant & Dietrich, 2017). Previous studies have shown how modification of the isotope input signal through dynamic mixing and fractionation provide additional insight into how water that infiltrates into soils, is subsequently evaporated or percolates deeper to recharge groundwater (e.g., Sprenger, Tetzlaff, & Soulsby, 2017). In
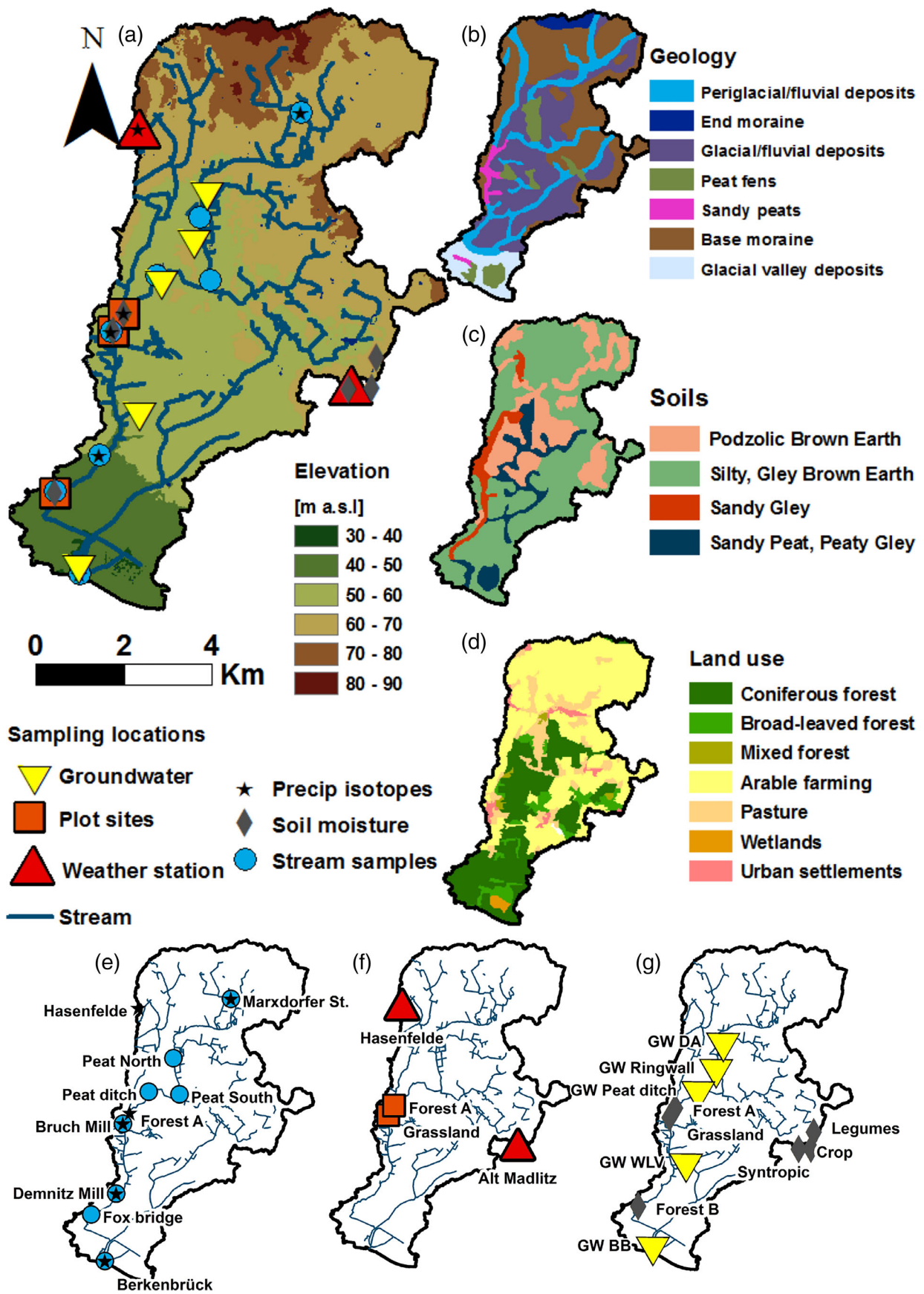
FIGURE 1 Maps of elevation, locations of measurements and sampling sites (a), geology (b), soils (c), land use (d), and detailed sampling locations (e–g) of the Demnitzer Millcreek catchment (DMC)

addition to such qualitative insights, tracers can provide a more quantitative assessment of the travel time between water entering the system as precipitation ("water age" = 0) and its exit fluxes from various stores (e.g., soil and groundwater compartments) or the entire catchment as streamflow. Moreover, the temporal and spatial dynamics in water ages in various critical zone compartments (Sprenger et al., 2019) help to understand how mixing involves different catchment storage characteristics (Soulsby et al., 2009), as well as illuminating the ecohydrological functioning of the landscape and resilience of the blue and green water fluxes (Kuppel et al., 2020).

The DMC, a tributary of the River Spree, is a long-term research catchment established in 1990 initially to understand agricultural influences on nutrient dynamics (Gelbrecht et al., 2005). Most of the catchment supports rain-fed agricultural systems, which face serious challenges in maintaining food production and other ecosystem services under likely climate change scenarios. Thus, recent years have seen a reorientation of research efforts to better understand the catchment's water balance and hydrological function. For example, the impacts of changes in wetland management and beaver re-colonization have been assessed (Smith, Tetzlaff, Gelbrecht, et al., 2020). Investigations of the impact of the drought 2018 on two contrasting soil-vegetation plot-scale units revealed land use dependent differences in the isotopic dynamics and age of soil water at the plot scale suggesting a higher drought resilience of forests (Kleine et al., 2020). Further, ecohydrological modelling presented differences in age dynamics of soil water and groundwater recharge between contrasting soil-vegetation assemblages (Smith et al., 2020b).

Here, we report an investigation that sought to up-scale insights from these initial plot-scale studies (Kleine et al., 2020; Smith et al., 2020b), through catchment-scale isotope monitoring of precipitation, soil water, groundwater and stream water over a >2-year period. This complemented and leveraged data from an existing, longer term hydrometric infrastructure. The study aimed to use isotopes to better understand the ecohydrological linkages between precipitation and spatial patterns of soil moisture, groundwater levels and streamflow generation at the catchment scale.

The specific objectives of the study were, to:

1. Characterize the spatio-temporal stable isotope dynamics in precipitation, soil water, groundwater and streamflow at the catchment scale.
2. Assess how different catchment characteristics (particularly land use) affect water partitioning, connectivity and the isotopic composition of soil, ground and stream water.
3. Understand how groundwater-surface water interactions and in-channel processes affect the isotopic dynamics of stream water, and the implications for water age estimates.

The wider implications of an improved understanding of vegetation and catchment responses to climate change (Babst et al., 2019) are also examined, as well catchment management for improving the resilience of ecosystem services in similar lowland landscapes is discussed.

2 | STUDY SITE

The study was conducted at the Demnitzer Millcreek catchment (DMC; 66 km^2) in NE Germany, which is a long-term experimental headwater site for hydrological and biogeochemical research at the Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB, Berlin, Germany). DMC is representative of the lowland and mixed land use landscape of the NGP (Smith, Tetzlaff, Gelbrecht, et al., 2020). The climate is characterized as mid-continental with annual precipitation (569 mm a^{-1}) being exceeded by annual potential evapotranspiration of 650–700 mm a^{-1} (Smith, Tetzlaff, Gelbrecht, et al., 2020). Precipitation occurs throughout the year with slightly more during summer when infrequent heavy convectional storms dominate. More frequent but lower intensity frontal rain prevails during the winter dormant period. The plain (<2% slope) landscape has an NNE – SSW orientation (Figure 1a). The catchment is characterized by complex hydrogeology formed during the last glaciation about 10–15 k years BP (Gelbrecht et al., 2005). The southern part is in a glacial meltwater valley with glacio-fluvial sediments prevalent extending from Warsaw to Berlin (Figure 1b), where the catchment outlet discharges water into Lake Dehmsee and subsequently into the River Spree. The more elevated northern part of the catchment is dominated by freely draining unconsolidated ground moraines, with glacio-fluvial sands and gravels prevalent in the South. Soils are freely draining and have a high fraction of sand (Table 1), though the northerly soils associated with the ground moraine have a higher silt content and retain more water (Figure 1c). Near the stream and in depressions, peat deposits are extensive and remain close to saturation throughout the year. Kettle holes are abundant as depressions in the landscape and are strongly influenced by groundwater (Nitzsche et al., 2017). These small water bodies provide important habitats and ecosystem services (Biggs et al., 2017).

The finer soils in the northern and eastern parts of the catchment are used for agricultural production (Table 1, Figure 1d). Multiple peatlands and fens exist along the stream network that are partly used as meadows. Land use gradually changes to forestry towards the southern region of the catchment (Figure 1d). Large parts of the catchment's forest cover are dominated by stands of Scots pine (*Pinus sylvestris*) which were intensively managed in the past. More recent management aims to enhance mixed and broadleaved forests (Lasch et al., 2002). The catchment has been historically drained, and fields in wetter areas are widely underlain with tile drainages. There is no irrigation being applied for agriculture. The anthropogenically influenced stream network (Nützmann et al., 2011) is highly drought-sensitive (Kleine et al., 2020) with flows being intermittent during dry periods (Smith, Tetzlaff, Gelbrecht, et al., 2020). Drainage and the connection of glacial hollows which formerly had no surface outflow expanded the channel network from 20 km (1790) to 88 km (Nützmann et al., 2011). This results in a transformed hydrology, channel morphology, aquatic habitats, and nutrient cycling (Blann et al., 2009). Overall, streamflow generation in the catchment is dominated by groundwater; the catchment has a strong seasonal flow regime, with highest flows generally in winter. Runoff coefficients

TABLE 1 Landscape characteristics of the eight weekly stream sample locations (altered from Smith, Tetzlaff, Gelbrecht, et al., 2020)

Site	Area [km²]	Farming [%]	Urban [%]	Pasture [%]	Broadleaf [%]	Conifer [%]	Mixed forest [%]	Wetlands [%]	Silty, Gley Brown Earth [%]	Podzolic Brown Earth [%]	Sandy Gley [%]	Sandy peat, Peaty Gley [%]
Marxdorfer St.	3.0	100	0	0	0	0	0	0	100	0	0	0
Peat North	18.5	82.4	2.1	11.2	0.1	3.3	0.9	0	75.0	15.6	0.9	8.6
Peat South	21.3	71.7	1.9	9.7	1	9.5	0.8	8.1	70.2	17.4	4.8	7.6
Peat ditch	25.7	70	1.2	6.5	0.9	17.4	0.3	3.6	68.0	18.5	5.2	8.3
Bruch Mill	40.7	68.2	2.1	7.4	1.2	17	0.6	3.5	69.5	18.7	4.6	7.2
Demnitz Mill	43.6	59.8	2.9	8.9	3.2	20.2	1	4	71.8	16.3	6.0	5.8
Fox bridge	48.6	54.9	2.6	7.5	2.5	28.9	0.7	2.8	80.3	11.5	4.2	4.0
Berkenbrück	66.4	50.4	2.5	6.9	6	29.2	1	4	70.7	20.7	3.8	4.9

during storm events are <5% indicating limited contributions from restricted areas of saturated or compacted soils, as well as sealed (urban/road) surfaces (Smith, Tetzlaff, Gelbrecht, et al., 2020).

3 | DATA AND METHODS

In addition to using long-term hydrometric data, we conducted multiple sampling campaigns to obtain spatially distributed samples of precipitation, throughfall, soil bulk water, groundwater, and stream water for water stable isotope analysis at the catchment scale. The sampling covers the period between January 2018 and April 2020. Due to the evolving sampling infrastructure and logistics, not all time series started simultaneously, and some were conducted for shorter periods (e.g., soil water isotopes). Nevertheless, good spatial coverage of the catchment was achieved. We used daily meteorological data of precipitation, mean air temperature and relative humidity at 2 m height from a nearby climate station (Müncheberg), which is operated by the German Weather Service (DWD, 2020). Automatic Weather Stations (AWS) were installed at Hasenfelde (WLV; Environmental Measurement Limited, UK; Figure 1f) in May 2018 and the eastern part of the catchment at Alt-Madlitz (Campbell Scientific, USA) in May 2019. The AWS recorded radiation, air temperature, precipitation, ground heat flux, and relative humidity at 15-min intervals.

Daily bulk precipitation sampling (from July 2018 onward) was conducted at the Hasenfelde AWS using a modified Autosampler (ISCO 3700, Teledyne Isco, Lincoln, USA) with an unshielded funnel 1 m above ground level. To assess for spatial variations in the isotopic composition of precipitation inputs, weekly rainfall samples were collected at four locations (from July 2018) along the stream network from rain gauges (Figure 1e; Marxdorfer St., Bruch Mill, Demnitz Mill, Berkenbrück). To assess potential canopy effects on the composition of net precipitation, throughfall was measured and sampled weekly in five randomly distributed gauges at Forest A (FA) (in a 10 by 10 m plot) and compared to the nearest open precipitation gauge Bruch Mill to assess interception loss. Both spatially distributed precipitation and throughfall collectors were installed at ground-level and collected at their height of ~30 cm. A layer of paraffin oil was added to all autosampler bottles and rain gauges to prevent evaporation (cf. International Atomic Energy Agency, 2014). Water was extracted from below the paraffin with a syringe, filtered (0.2 μm, cellulose acetate) in the field and cooled (8°C) until further analysis.

Two soil moisture monitoring locations, were installed near the stream monitoring point at Bruch Mill (Figure 1g; FA and Grassland [GS]) in June 2018 (Kleine et al., 2020). FA is an oak (*Quercus robur*) dominated stand. Four additional soil moisture stations were installed in March 2019: under a mature broadleaf forest site (Forest B, FB); a conventionally managed crop site (Crops); a site planted with legumes in combination with a periodic grazing of cattle (Legumes); and a site that is currently transformed into an agroforestry with a combination of crops (Syntropic). The loggers recorded volumetric water content every 15 min. Sites FA and GS were each equipped with 36 combined FDR (ring oscillator) soil moisture and temperature probes (SMT-100,

Umwelt-Geräte-Technik GmbH, Müncheberg, Germany), which were installed at three depths (20, 60 and 100 cm, five replicates). Time Domain Reflectometry (TDR) probes (CS-650, Campbell Scientific, USA) were installed at sites FB (at 10, 25, 50, 100 cm), Legumes (at 15, 35, 60, 100 cm), Crops (at 15, 40, 60, 100 cm), and Syntropic (at 20, 40, 80 cm; all with two replicates at each depth). Two of the soil moisture sites (GS, FA) were used to also characterize spatial and temporal variation in bulk soil water isotope signatures. For this, monthly destructive sampling was conducted manually with a soil auger from September 2018 to October 2019. The soil profile was segmented into six depths (0–5; 5–10; 10–20; 20–30; 40–60; 80–100 cm) from which we took three samples per depth at each site. Samples were immediately placed in diffusion-tight soil sampling bags (CB400-420siZ, WEBER Packaging GmbH, Güglingen, Germany).

Five groundwater wells were sampled (GW, Figure 1g); these are located along the main stream network in close spatial proximity to the stream (within 10–400 m). GW DA (screening dimensions below surface level unknown) is the most northern well and located north of the main peat fen, which the stream network traverses. Other groundwater locations close by are located in a forest west of the fen (GW Ringwall; screened 2.62–3.65 m below surface) and after the fen (Peat ditch; screened 3.50–5.57 m). Well GW WLV (screened between 2.50–3.00 m) was included in December 2018 and is located south of the village Demnitz. The most southerly well (GW BB, screened depth unknown) is located near the catchment outlet in the glacial melt water valley. Two (GW Ringwall; GW Peat ditch) of the five wells were equipped with dataloggers (AquiLite ATP 10, AquiTronic Umweltmeßtechnik GmbH, Kirchheim/Teck, Germany) recording water levels every 4 h (precision of <1%, resolution of 1 mm). GW WLV records hourly water levels. Groundwater levels at GW DA and GW BB were measured manually when taking isotope samples. Groundwater was sampled monthly for stable water isotopes, extracting at least twice the volume of water sitting in the well with a pump (COMET-Pumpen Systemtechnik GmbH & Co. KG, Pfaffschwende, Germany) before taking a filtered (0.2 μm, cellulose acetate) sample back to the laboratory.

Discharge at Demnitz Mill was determined by transferring water level records (AquiLite ATP 10, AquiTronic Umweltmeßtechnik GmbH, Kirchheim/Teck, Germany) using a rating curve established by Smith, Tetzlaff, Gelbrecht et al. (2020). Eight stream isotope sampling locations were nested along the catchment's stream network (Figure 1e). The sampling sites ranged from the source area (Marxdorfer St. (1)) upstream of the first major fen (Peat North (2)), in the middle of the fen (Peat South (3)) and downstream of the fen and small connected ponds, which are relics of historical peat extraction (Peat ditch (4)). The next downstream location Bruch Mill (5) is close to the terrestrial ecohydrological monitoring sites of GS and FA (Figure 1f,g). Upstream of the glacial valley is the sampling location Demnitz Mill (6) followed by site Fox bridge (7), which is near the terrestrial ecohydrological site of FB (Figure 1g). The Demnitzer Millcreek then reaches the catchment outlet at Berkenbrück (8). Samples were taken weekly if stream water was present, but data gaps occurred due to the cessation of flow during dry periods. All stream water samples of a given date were taken within a few hours. Some sites (Peat South (3), Demnitz Mill (6), Berkenbrück (8)) were influenced by beaver dams downstream or directly upstream, and thus, had water for longer time periods. Water was sampled at the centre of the stream in a 1-litre bottle and cooled (8°C) after filtration (0.45 μm) before subsequent isotope analysis. Under non-flowing conditions, sites with ponded water were only sampled sporadically for isotopic composition.

The ratio of the heavy stable isotopes of hydrogen (deuterium, δ^2H) and oxygen (oxygen-18, $\delta^{18}O$) to their more common lighter isotopes (protium, oxygen-16) in water samples was determined in the isotope laboratory of IGB relative to the Vienna Standard Mean Ocean Water (VSMOW). Liquid samples of precipitation, throughfall, groundwater, and streams were analysed using cavity ring-down spectroscopy (CRDS, L2130-i, Picarro, Inc., CA, USA). ChemCorrect Software (Picarro, Inc., CA, USA) was used to identify samples contaminated with organics. Soil bulk water was analysed using a modified version of the direct-equilibrium (DE) method (Wassenaar et al., 2008). We introduced dry synthetic air as headspace to the bags containing the sampled bulk soil (see above) and additionally to three liquid standards in identical bags (10 ml, known isotopic compositions) upon return from the field. After ~48 h of equilibration in thermally stable conditions, the headspaces of samples and standards were measured by CRDS. The soil water results from the headspace were referred to the liquid phase using the liquid standards, which were handled like the samples, following the principle of identical treatment. We corrected for artefacts caused by gas matrix changes in the headspace (Gralher et al., 2018).

As the anticipated processes leading to variations in sampled water isotopic signatures (fractionation and mixing) are affecting both $\delta^{18}O$ and δ^2H, here we choose to mainly show $\delta^{18}O$ signatures in plots to avoid redundancy and keep plots simple (though δ^2H are presented in dual isotope plots). To assess evaporation effects on the isotopic composition of samples, we calculated deuterium excess as suggested by Dansgaard (1964):

$$d\text{-excess} = \delta^2H - 8 \cdot \delta^{18}O \qquad (1)$$

We further calculated the line-conditioned excess (short lc-excess) defined by Landwehr and Coplen (2006) which defines the unconformity with the local meteoric water line (LMWL) as:

$$lc\text{-excess} = \delta^2H - a \cdot \delta^{18}O - b \qquad (2)$$

where a is the slope and b the intercept of the local amount weighted precipitation (DMC: a = 7.89; b = 8.62).

Mean transit times (MTTs) for stream sites were calculated by weighting weekly precipitation $\delta^{18}O$ signatures inputs with a time-invariant gamma distribution to model stream water isotopic signatures. Best fits were determined by a maximum Kling-Gupta Efficiency (KGE; Gupta et al., 2009) within the predefined parameter ranges for the shape factor (α; 0.1 to 2.5) and the scale parameter (β; 2 to 500). MTT uncertainties are presented as the SD of the fitted MTT. To
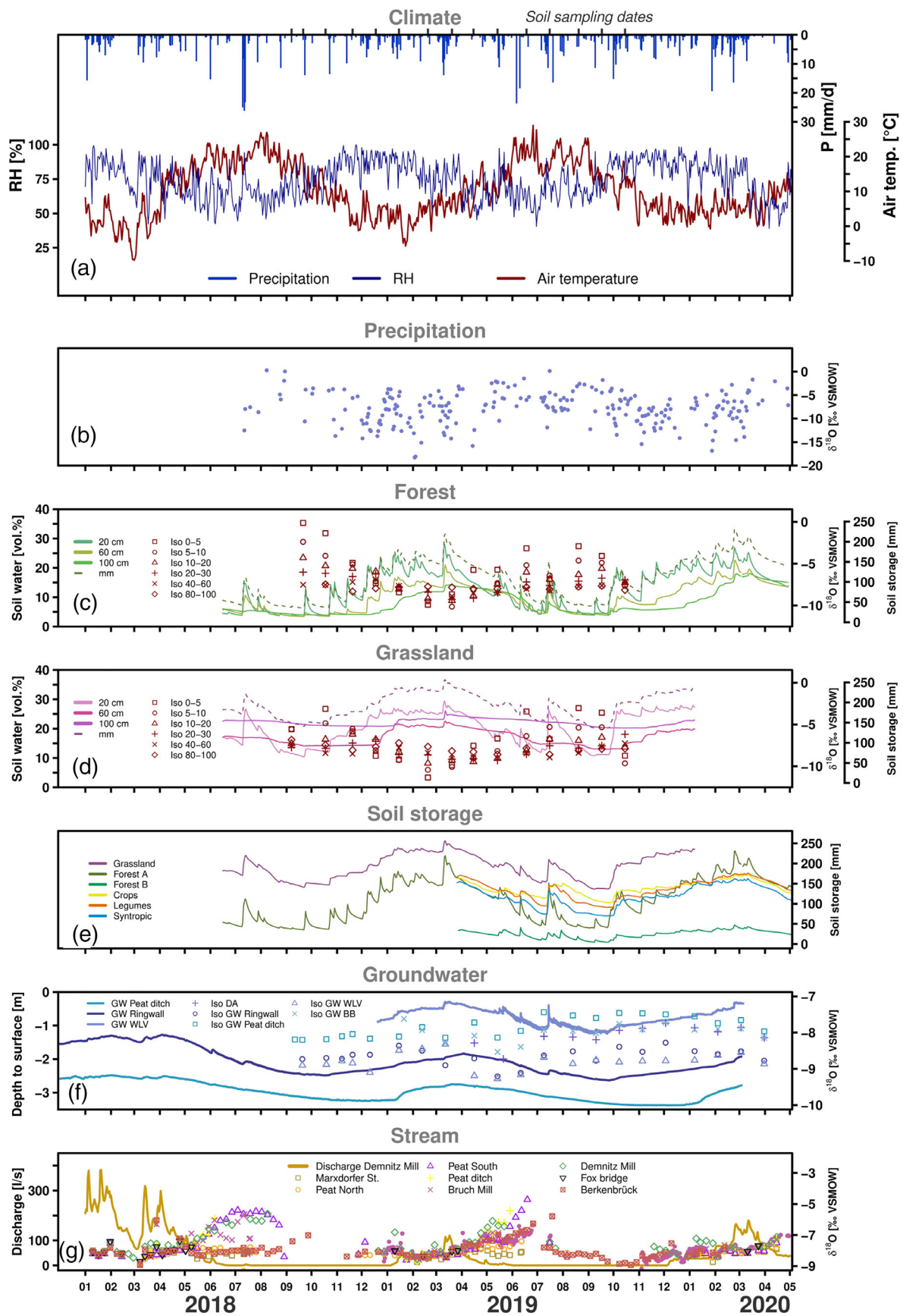
FIGURE 2 Timeseries of DWD precipitation, relative humidity and air temperature (a); daily precipitation and δ^{18}O at Hasenfelde (b); soil moisture (at 3 depths) and bulk soil water δ^{18}O (at 6 depths) and soil storage in the first meter of the forested (c); and grassland site (d); soil storage for all five soil moisture locations (e); groundwater levels and δ^{18}O signature (f); discharge and spatial weekly stream water δ^{18}O (g)

assess the young water fraction (YWF) in stream water, we applied the iteratively re-weighted least squares fitted sine-wave method (Von Freyberg et al., 2018). The ratio of amplitude values derived from the seasonal cycle of precipitation and stream represent the estimated fraction of water in streams that fell as precipitation within the last ~2–3 months (Kirchner, 2016). Uncertainties in the YWF were derived from maximum ranges from variables SE of the YWF fit. We compared sine-wave fit amplitudes of monthly amounts of weighted open precipitation $\delta^{18}O$ signatures from the source area (Marxdorfer St. (1)) to stream samples at the other nested locations. Calculations were done in R (R Core Team, 2018, version 3.5.0) with publicly available code by von Freyberg et al. (2018). All samples with an evaporative signal (lc-excess < −5‰) were excluded from the MTT and YWF analysis to avoid misinterpretations from likely in-stream open water fractionation rather than precipitation input variability. Spatial patterns of precipitation amount and isotopic signature (Figure 3) were created using interpolation with inverse distance weighting (IDW, Arc Map 10.5).

Soil water storage (as mm water column in the first meter) of the soil profile were estimated by weighting the measured volumetric soil moisture according to depth. Depending on the number of sensors, the profile was subdivided in segments that were assumed to be represented by each sensor. This simple method allowed estimating the soil storage as volumetric percentage from the total (1000 mm) soil profile for inter site comparison.

4 | RESULTS

4.1 | Spatio-temporal dynamics in precipitation amount and isotopes

Daily temperature and relative humidity (Figure 2a) both showed a pronounced seasonal variation during the two study years. Mean daily air temperatures ranged between −9.8°C (winter) and 29.0°C (summer). Conversely, relative humidity varied between a low 39% in the growing season and high 100% in winter. Precipitation occurred year-round with less frequent, larger events during summer and more frequent, lower intensity events during winter (Figure 2a). Precipitation amounts during the main study period reflected the drought conditions, with the total precipitation in 2018 (386 mm a^{-1}) being ~30% and in 2019 (440 mm a^{-1}) ~23% below the long-term mean annual precipitation (569 mm a^{-1}; 1990–2018, for details see Smith, Tetzlaff, Gelbrecht, et al., 2020). Precipitation was generally slightly higher during summer relative to winter.
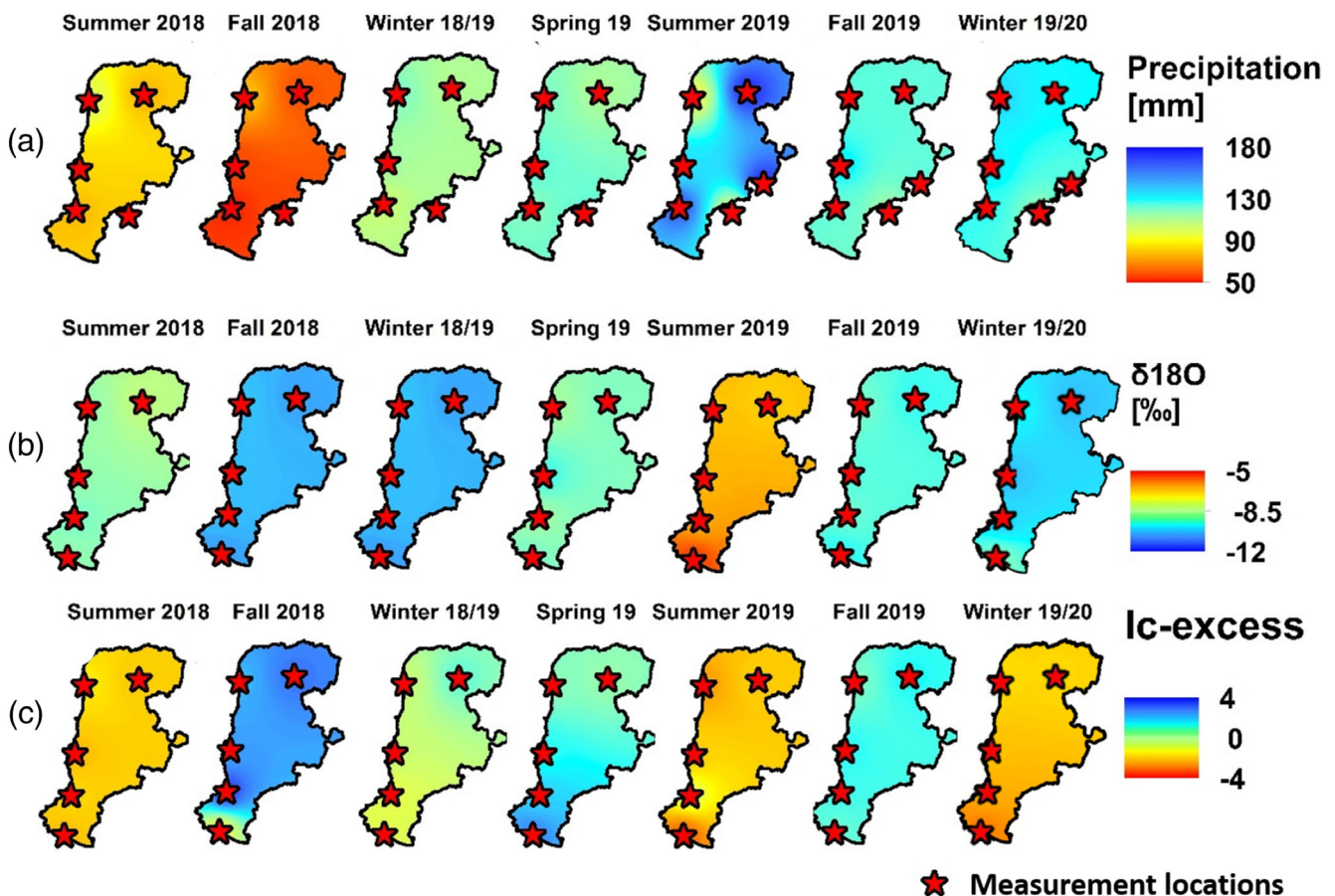

FIGURE 3 DMC spatial and seasonal (see Table 1) precipitation patterns of precipitation amounts (a), $\delta^{18}O$ signature (b), and lc-excess (c)

TABLE 2 Details of the seasonal precipitation shown in Figure 3 including precipitation seasons, sums, SD and its weighted mean (w.mean) and SD of $\delta^{18}O$ and lc-excess values

Season	Date		Precipitation		$\delta^{18}O$ [‰]		lc-excess [‰]	
	From	To	mean	SD	w. mean	SD	w. mean	SD
Summer 2018	10.07.2018	29.08.2018	86.9	9.1	−8.8	0.26	−1.9	0.21
Fall 2018	30.08.2018	27.11.2018	61.9	10.4	−7.3	0.29	2.1	1.56
Winter 18/19	28.11.2018	26.02.2019	117.4	5.4	−10.3	0.16	−0.2	0.62
Spring 2019	27.02.2019	28.05.2019	119.3	4.7	−9.0	0.32	1.3	0.83
Summer 2019	29.05.2019	27.08.2019	128.6	21.1	−6.4	0.55	−1.9	0.80
Fall 2019	28.08.2019	26.11.2019	130.0	5.8	−9.4	0.18	1.1	0.25
Winter 19/20	27.11.2019	24.02.2020	134.8	6.5	−9.9	0.48	−2.1	0.42

The seasonality in hydroclimate was reflected in the variations in $\delta^{18}O$ in daily precipitation (Figures 2b and 3b) with heavier $\delta^{18}O$ signatures in summer precipitation (max = 0.3‰) than winter precipitation (min = −18.3‰). However, large day to day variability obscured a seasonal pattern, and there was an overall SD of 3.4‰.

Spatial differences in precipitation amounts across the entire catchment were limited compared to the temporal dynamics over the seasons (Figure 3a). Spatial differences in the isotopic composition of rainfall were only evident during convective summer events, when differences in precipitation amounts were also higher as a result of more localized storm cells. However, these event-based variations were minor when aggregated over longer (seasonal) time scales (Table 2).

Cumulative precipitation amounts (Figure 4a) across the catchment varied little over the study period. However, differences in total accumulated amounts between the nearest open precipitation (Bruch Mill (5); 854 mm) and throughfall (FA 1–5; 592 mm) measurements were 31%. Mean interception loss at FA (Figure 4b) peaked with 92% during a small summer precipitation event (0.5 mm) while some measurements in the dormant season showed no difference. Percentage interception loss during the sampling period derived from the five samplers was smallest in summer (mean: 22%; SE: 2.8%) and winter (29%; 1.4%), higher in autumn (33%; 2.5%) and highest in spring (43%; 2.2%). In contrast to the precipitation amounts, the isotopic signatures of open precipitation and throughfall (Figure 4c,d) were very similar for most sampling campaigns.

4.2 | Spatio-temporal dynamics in soil water, groundwater and discharge and their isotopic signatures

The soil moisture content at FA varied seasonally at all depths with maxima in winter and minima during the summer of 2018 (Figure 2c). The upper soil moisture measurements showed wetter conditions and short-term responses to individual precipitation events (mean = 13.0%; SD = 6.6%). The soils were drier, and dynamics were more damped and lagged at 60 cm (mean = 9.9%; SD = 4.9%) and 100 cm depth (mean = 8.3%; SD = 4.2%). Monthly isotope signatures in the bulk soil water at FA also displayed seasonal signals, with more negative mean

profile $\delta^{18}O$ (−9.0‰) values in March 2019 and more positive values at the end of summer (−5.3‰; October 2018; September sampling 5 depths: −4.1‰). This seasonal signal was also more damped with increasing depth (SD $\delta^{18}O$: 2.5 cm = 2.9‰; 15 cm = 1.6‰; 50 cm = 0.6‰; 90 cm = 0.2‰). The soil at GS (Figure 2d) was wetter but had similar seasonality in soil moisture and bulk water $\delta^{18}O$, but with less variability for both. SD in bulk soil water $\delta^{18}O$ at GS also decreased with depth (SD $\delta^{18}O$: 2.5 cm = 2.7‰; 15 cm = 1.2‰; 25 cm = 0.9‰; 50 cm = 0.6‰; 90 cm = 0.5‰).

Water stored in the upper meter of the soil at the five soil moisture stations (Figure 2e) showed further seasonal variations and spatial differences. Highest values occurred during rewetting in spring 2020. However, at GS soil storage reached its maximum in March 2019. Highest values in stored water ranged from 25 mm at FB to 256 mm at GS (FA = 108 mm; Crops = 173 mm; Legumes = 176 mm; Syntropic equals; 162 mm) which reflects differences in landcover and soil characteristics. Minima in soil storages occurred during the end of summer 2019 at all sites but FA, which timeseries started earlier, with its lowest values (37 mm, 22.10.2018) during the drought of 2018. Responses of soil water storage to precipitation events occurred during summer and winter, but subsequent drying was much faster after events in the growing season. The inter-site differences in soil water storage during the period with all stations operating (28.03.2019–07.01.2020) ranged from 21 mm at FB to 192 mm at GS (FA = 97 mm; Crops = 132 mm; Legumes = 126 mm; Syntropic = 108 mm).

Groundwater levels (Figure 2f) strongly reflected the deficits in DMC water storage resulting from the drought in 2018 and only partial recovery in early 2019. Even at the end of the study and two winter recharge periods, groundwater levels were lower than in early 2018. All sites displayed seasonal variation, but minima occurred at different times (WLV and Ringwall in September 2019; Peat ditch in January 2020). Maxima occurred in the first half of the year (WLV in March 2019, Ringwall in April 2018; Peat ditch in January 2018). Recharge is mainly restricted to winter with seasonal depletion of the storage following the start of the vegetation growth period. The five wells monitored for isotopes differed in their mean $\delta^{18}O$ values (ranging between −7.8‰ at Peat Ditch and −8.8‰ at WLV). However, all wells had similar variability over the same period in their $\delta^{18}O$ (SDs of

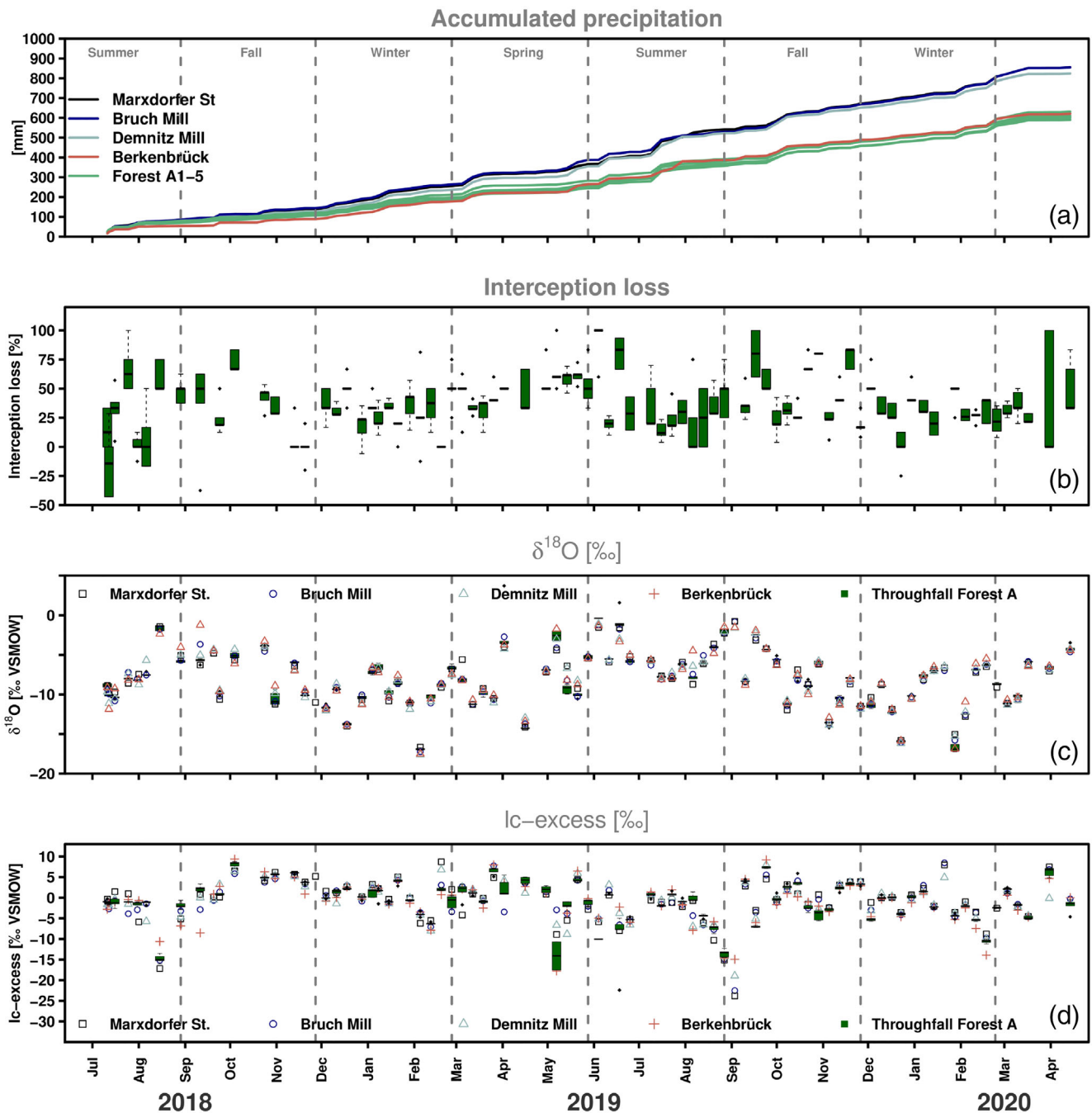**FIGURE 4** Accumulated precipitation (a), interception loss relative to open precipitation sampler (b), $\delta^{18}O$ (c) and lc-excess (d) of the DMC spatial precipitation samplers

~0.2–0.3‰), which was notably lower than for even the deepest soil horizons.

Measured stream discharge at Demnitz Mill (6) (Figure 2g) was highest at the start of the study. All stream sampling sites had intermittent flows during the study, ceasing in summer. Discharge at Demnitz Mill (6) occurred only during the first half of the sampling years (421 days out of 771), corresponding to times when groundwater levels (Figure 2f) were higher. The stream water $\delta^{18}O$ signatures showed seasonality at all locations but were much more damped than the precipitation signal. Variability in stream $\delta^{18}O$ was low (and similar

to groundwater) in the upper catchment (SD: Marxdorfer St. (1) = 0.3‰; Peat North (2) = 0.3‰), but increased within the peat fen (SD Peat South (3) = 1.1‰) and then decreased at the downstream locations of Peat ditch (4) (SD = 0.8‰) and Bruch Mill (5) (SD = 0.7‰). Demnitz Mill (6) samples again were characterized by higher dynamics (SD = 1.4‰) that were not evident in the downstream locations at Fox bridge (7) (SD = 0.3‰) and Berkenbrück (8) (SD: 0.8‰). At Peat ditch (4) (n = 38) and Fox bridge (7) (n = 22) stream water was frequently absent due to drought conditions causing long gaps in the isotopic dataset.

4.3 | Landscape influences on isotope fractionation processes

Along the catchment's N-S gradient there is an increasing percentage of forest along the river corridor (Figure 1d and Table 1) downstream from the source area. Bulk soil water isotopic composition and soil moisture under the two land use units (forest and grassland) varied over time and between soil/vegetation classes indicating differences in groundwater recharge fluxes (Figure 2). Overland flow or standing water was not observed during the study period.

The isotopic signatures of the different water components and between sampling sites showed clear differences in ranges and deviations from the LMWL (Figure 5). Precipitation (Figure 5 inset) samples plotted on the LMWL covering a wide range of isotopic compositions (δ^{18}O = −18.3‰ to 0.3‰; δ^2H = −140.2‰ to −4.1‰). All other samples displayed lower variability. Values in bulk soil water ranged from −11.3‰ to −0.1‰ for δ^{18}O and − 84.8‰ to −21.1‰ for δ^2H, deviating from the LMWL and indicating evaporative fractionation processes in the upper soil horizons, whilst the deeper soil horizons plotted closer to groundwater. Groundwater signatures from GW Ringwall plotted close to the LMWL and were very stable (δ^{18}O = −9.2‰ to −8.3‰; δ^2H = −61.0‰ to −57.5‰), most closely resembling winter precipitation. Stream water samples during winter were generally similar to groundwater, with differing degrees of deviation from the LMWL between sites. The agriculture-dominated headwater sites upstream of the peatland showed little deviation (Marxdorfer St. (1)), whilst the locations in the peatlands (Peat South (3)) and downstream (Bruch Mill (5), Berkenbrück (8)) deviated along a similar slope indicating fractionation effects.

Looking at the individual stream sites in more detail, locations upstream of the peatland (Marxdorfer St. (1), Peat North (2); Figure 6a,b) with highest relative areas of farming and limited wetland influence (Table 1) deviated little from the groundwater signal in the dual isotope plot. In comparison, the downstream locations with increasing wetland influence (Peat south (3), Peat ditch (4)) were more enriched with greater deviations from the LMWL. This was less

marked at Bruch Mill (5) just downstream of an agricultural tributary inflow. At Demnitz Mill (6), stronger variability and more marked fractionation resembled the characteristics of Peat South. Subsequent stream sampling locations in the forested glacial meltwater valley (Fox bridge (7) and Berkenbrück (8)) showed very different characteristics. At Fox bridge (7), a low number of samples ($n = 22$), mostly from winter, deviated little from the LMWL and the groundwater signal. Stream water at Berkenbrück (8), in contrast, was always present due to the presence of multiple beaver dams up- and downstream of the sampling location. Whereas most stream samples here plotted close to the GW Berkenbrück signal, some deviations occurred (SD lc-excess [SD_{lc}] = 2.5‰) but this was less frequent and pronounced than at Peat South (3) ($SD_{lc} = 3.4$‰) and resembled the dynamics at the Bruch Mill (5) location more ($SD_{lc} = 2.6$‰).

The temporal dynamics of the stream samples (Figure 7) displayed strong differences in the frequency of flowing water and isotopic fractionation signals throughout the study period. The dynamics of lc-excess (Figure 7) were minor at Marxdorfer St. (1) ($SD_{lc} = 1.1$‰) and Peat North (2) ($SD_{lc} = 1.1$‰) with both sites lacking the pronounced drop in lc-excess that the other sites showed in summer, prior to running dry. After the stream passes into the peat fen and associated beaver-impacted wetlands, Peat South (3) exhibited strong deviations from precipitation and the local groundwater, mainly during the summer. The marked dynamics in lc-excess at Peat South (3) ($SD_{lc} = 3.4$‰) were also apparent but less pronounced in the subsequent downstream sampling locations Peat ditch (4) ($SD_{lc} = 2.6$‰) and Bruch Mill (5) ($SD_{lc} = 2.6$‰). Demnitz Mill (6) stream water isotopic composition, affected by beaver dams immediately upstream, again showed more deviation from the LMWL at low and no flow conditions in the vegetation period (Figure 7g) resulting in overall higher dynamics ($SD_{lc} = 7.2$‰). The highly ephemeral downstream flows at Fox bridge (7) showed no strong dynamics in lc-excess ($SD_{lc} = 1.3$‰), whereas the catchment outlet (Berkenbrück (8)) gave the highest sampling number ($n = 88$, Figures 2f, 6h and 7i) with low variability in lc-excess (SD = 2.5‰) deviating from the LMWL gradually with some events causing a return to less pronounced lc-excess.
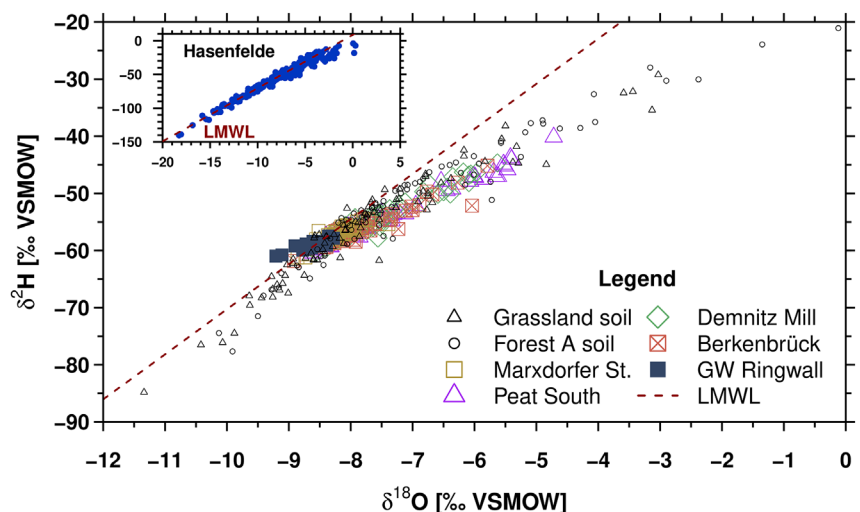

FIGURE 5 Dual isotope plots of the daily precipitation (inset), bulk soil water, stream and groundwater Ringwall samples and the local meteoric water line (LMWL)
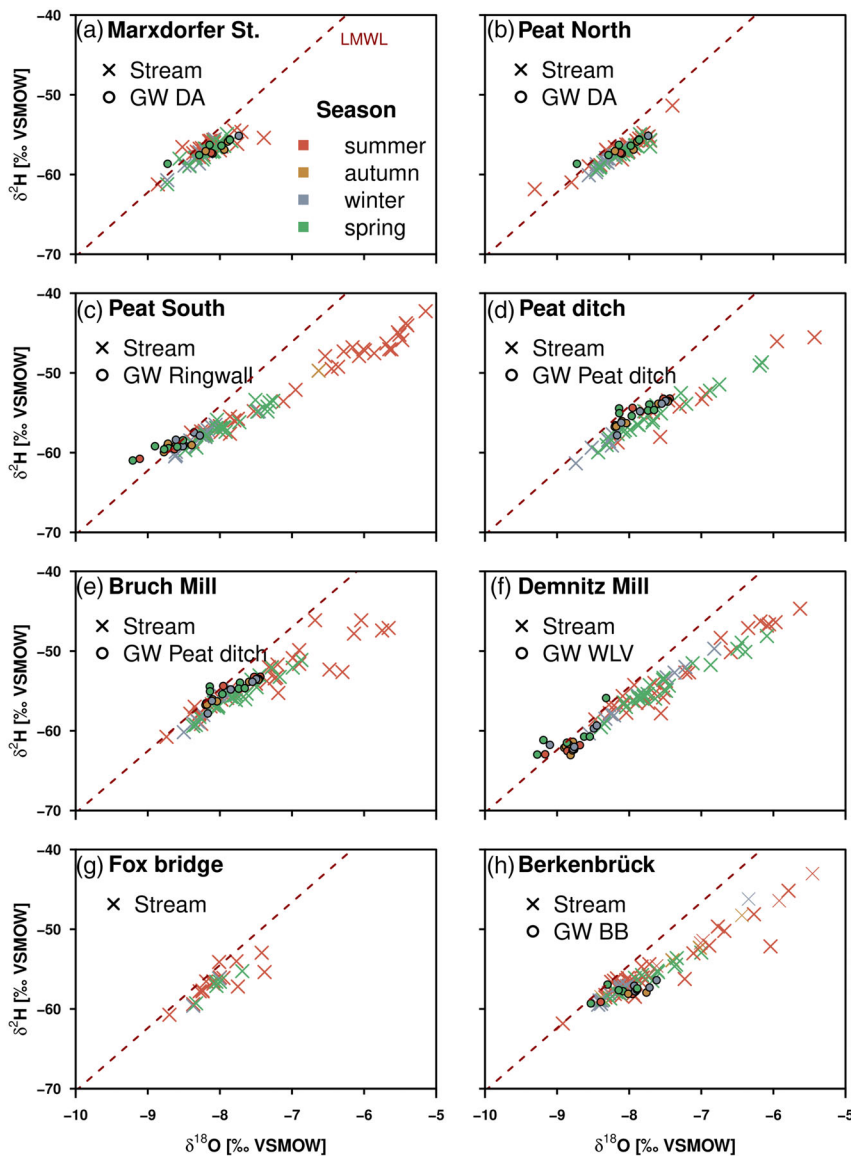
FIGURE 6 Dual isotope plots of weekly stream samples and nearest groundwater site coloured by season in order from headwater to catchment outlet (a–h)

4.4 | Effects of riparian land use and in-stream processes on the isotopes and implications for age estimates

It was striking how the locations (1 and 2) sampled upstream of the peatland had little influence of open water evaporation on the isotope composition and low lc-excess (Figures 6 and 7). Equally the influence of the wetlands in the peat fen resulted in marked enrichment with fractionation dominating the isotopic signatures in stream water at most downstream sites, especially during low flow periods when water residence times in the wetlands are likely to be longer. As a result, attempts to estimate the ages of stream water in Demnitzer Millcreek need to acknowledge the potential impacts of fractionation signals on resulting young water fractions or MTT.

At the most northern and agriculturally dominated subcatchment of Marxdorfer St. (1), the YWFs derived from the isotope variations were low (2.3%) and estimated MTTs were highest of all sites at 4.6 years (Table 3). The more complex catchment structure with increasing scale and more marked anthropogenic influences (e.g., drainage and urban areas) at the downstream stream sampling site Peat North (2) resulted in a higher YWF (13%) and reduced MTTs to ~3.5 years. Subsequent sites showed increasing YWFs and decreasing MTTs but with lower alpha values (Table 3). The "apparent" YWF increase (YWF = 51%) and MTT decrease (MTT = 0.2 a) at Demnitz Mill (6) is presumably an artefact of fractionation driven stream isotope variability, rather than representing a decrease in water age. Water was always present at Berkenbrück (8), even when disconnected from the surface stream network. The strong groundwater effect resulted in a strong damping of the isotopic precipitation signal, with low YWF (6.5%) even though the MTT (3.0 a) remained lower than at Marxdorfer St.
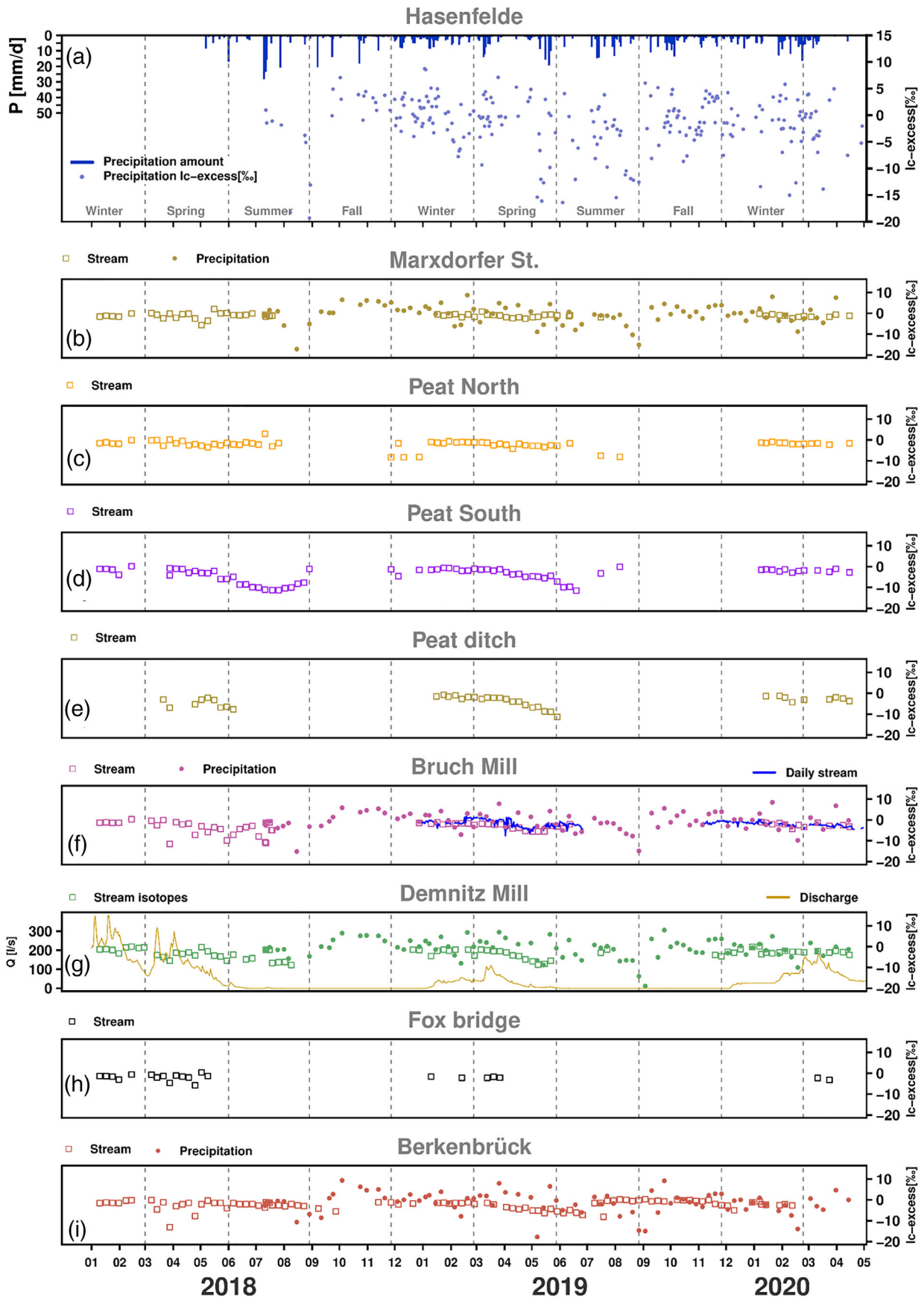
FIGURE 7 Precipitation and stream lc-excess of spatial distributed DMC sampling locations from headwater to outlet (a–i)

TABLE 3 Young water fraction and related *p*-value (significance) of the fitting and ranges from SEs in the parameters mean transit time (MTT) estimations and related fitting efficiency and parameters alpha and beta for the DMC stream sampling sites

Site	Young water fraction δ¹⁸O			MTT (gamma distribution) δ¹⁸O				
	Fraction [%]	*p*-value	Range min-max [%]	MTT [a]	KGE	SD	alpha (0.1–2.5)	beta (2–500)
Marxdorfer St.	2.3	5.8E-01	1.6–10.2	4.6	0.0	1.2	0.5	500
Peat North	12.8	6.1E-09	7.6–23.9	3.6	0.3	2.3	0.4	500
Peat South	21.4	3.2E-10	12.2–39.5	0.8	0.4	3.3	0.1	438
Peat ditch	26.8	7.7E-06	14.9–50.0	1.1	0.5	1.4	0.1	500
Bruch Mill	37.1	6.0E-14	21.8–66.8	1.6	0.7	1.9	0.2	500
Demnitz Mill	51.2	1.4E-09	29.7–92.8	0.2	0.5	2.4	0.1	97
Fox bridge	22.8	1.6E-01	6.2–58.2	0.1	0.4	2.5	2.5	2
Berkenbrück	6.5	4.0E-03	2.9–15.3	3.0	0.5	2.3	0.3	459

5 | DISCUSSION

5.1 | Insights into hydrological process dynamics from water stable isotopes of the DMC

The overarching aim of this study was to use water isotope signatures of different compartments of the critical zone to provide an improved understanding of the hydrological functioning of the DMC, which is representative of many lowland headwater catchments of the NGP and the North European Plain. For almost three decades, research in the DMC catchment was mostly focused on water quality issues (Dieter et al., 2011; Gelbrecht et al., 1998, 2005; Gücker et al., 2014). However, given the urgency of climate change, the consequences of riparian restoration and beaver population recovery, and the closely coupled nature of biogeochemical processes and ecohydrological pathways, it became clear that more detailed hydrological understanding was needed at the catchment scale. Though it was not foreseen that the study period included one of the driest spells in the catchment's monitoring history, this provided a preview of future hydroclimatic conditions in the region under climate change (Lüttger et al., 2011). Despite the lower-than-average rainfall and higher-than-average temperatures, the seasonal distribution of precipitation was characteristic in terms of less frequent, high intensity summer rainfall events, and more frequent, low intensity winter rain (Smith et al., 2020b). Precipitation in this flat landscape was generally spatially uniform, as often assumed but rarely examined in landscapes without major terrain features (Daly, 2006).

Whilst previous ecohydrological studies in the catchment focused on the plot-scale (Kleine et al., 2020; Smith et al., 2020b), water isotope signatures can also provide a more spatially integrated understanding of hydrological function at the catchment scale (Kendall & Mcdonnell, 2012). Similar to the precipitation amount, the spatial variation in the isotopic composition of rainfall was limited relative to the spatial scale (Bowen & Revenaugh, 2003). Pronounced deviations only occurred at the catchment outlet at Berkenbrück, which reflected the influence of land use (forest) on net precipitation isotopic composition rather than spatial variations in open precipitation. Isotopic transformations in throughfall can be complex and substantial (Allen

et al., 2017), however, canopy effects in DMC were limited and restricted to small summer events. This presumably reflects the DMC's high intensity summer precipitation, the canopy structure of the sampling site FA, the sampling frequency and that no stem flow was considered (which was largely negligible in the forest plots). Such limited canopy effects were also recently reported for Scots Pine forests in Scotland (Soulsby et al., 2017).

Bulk soil water isotopes reflected differences in vegetation cover, soil water use and soil characteristics. The free-draining soils under forest (FA) showed a stronger influence of recent precipitation and stronger evaporation effects due to lower net rainfall and limited water storage. Under grassland, the dynamics were similar but less pronounced for bulk soil water. This was also reflected in the soil moisture profiles under both land uses, indicating vegetation and soil dependent water dynamics and age distributions (Smith et al., 2020b).

Observed variability in shallow groundwater isotopes were directly and indirectly influenced by spatial patterns of groundwater recharge at the catchment scale (Lewandowski et al., 2009; Zimmer & McGlynn, 2017a). Previous isotope-based modelling of the dynamics in water ages (Smith et al., 2020b) showed that forest cover results in lower and older recharge to the near-surface groundwater system that feeds streamflow. This is in accordance with other assessments that predict negative trends in groundwater recharge under changing forest and climate characteristics in the region (Natkhin et al., 2012). Furthermore, low groundwater levels during the dry study period could indicate local groundwater recharge from surface waters, with streams seasonally switching to losing conditions (Nitzsche et al., 2017). This is a common transient phenomena and can have a greater influence than vegetation water use in local groundwater recharge dynamics (Krause et al., 2007), though the process is reversed during wetter conditions when groundwater gradients are likely to be towards the stream (Zimmer & McGlynn, 2017a).

The isotope data also provided evidence that groundwater and riparian storages-flux relationships can be dynamic in space and time in lowland landscapes (Krause et al., 2007) showing limited variability in stream water isotopes during winter, when groundwater levels are high and closely overlap with wells near-by. Summer fractionation is

not inconsistent with groundwater-dominance but simply indicates that open water evaporative fractionation affects the stream network where peatlands (Sprenger, Tetzlaff, Tunaley, et al., 2017), particularly with beaver dams, are present and provide large open water surfaces (Rosell et al., 2005). Isotopes, thus, have helped to underpin a conceptual model of this groundwater-dominated, lowland catchment; identifying spatial variability in ecohydrological partitioning under differing water storage states that can guide future research efforts, and support more quantitative modelling (Birkel et al., 2011).

5.2 | Landscape influences on water partitioning and connectivity

The interplay of interception, rooting depth, transpiration, soils and artificial drainage results in vegetation having a strong influence on spatial patterns of groundwater recharge amounts and timing at the catchment scale (Smith et al., 2020a). The dynamic ecohydrological partitioning of precipitation into groundwater recharge and ET alters seasonal hydraulic gradients in the subsurface under contrasting dominant vegetation types in the DMC (Smith et al., 2020a), with recharge being lower under forest than grassland (cf. Douinot et al., 2019). Resulting spatial patterns of groundwater discharge in riparian areas are important for sustainable management (Gou et al., 2015), biotic communities (Fritz & Dodds, 2004; Larned et al., 2010) and the

transport of organic matter and nutrients (del Campo et al., 2020; Stieglitz et al., 2003).

The effects of groundwater-surface water interactions on catchment runoff were modulated by the high summer ET losses, which resulted in prolonged periods of discontinuous streamflows in summer and below average winter runoff. Nevertheless, the synchrony of the soil re-wetting by autumn rainfall with rising groundwater levels and re-establishment of connectivity in the channel network was consistent with the findings of previous work which emphasized the dominant role of groundwater in streamflow generation in DMC (Nützmann et al., 2011; Smith, Tetzlaff, Gelbrecht, et al., 2020).

Of course, the dynamics of the stream network are related to underlying runoff generation processes (Garbin et al., 2019) as well as the groundwater and riparian storages-flux relationships that can be highly dynamic in lowland landscapes (Krause et al., 2007).

Spatially, the upper catchment of the DMC is strongly dominated by agriculture. Following the main stream channel southward, through the main area of central wetlands, the catchment landcover gradually becomes dominated by coniferous forests (Figure 1d). These forests are associated with higher green water fluxes and reduced recharge as indicated by soil moisture and isotope dynamics. Whilst the stream network is well-connected with continuous flow at all sites during the winter, disconnection begins in the spring. These changing landscape influences with changing connectivity are conceptualized in Figure 8, highlighting the heterogeneity and seasonal variation in surface water
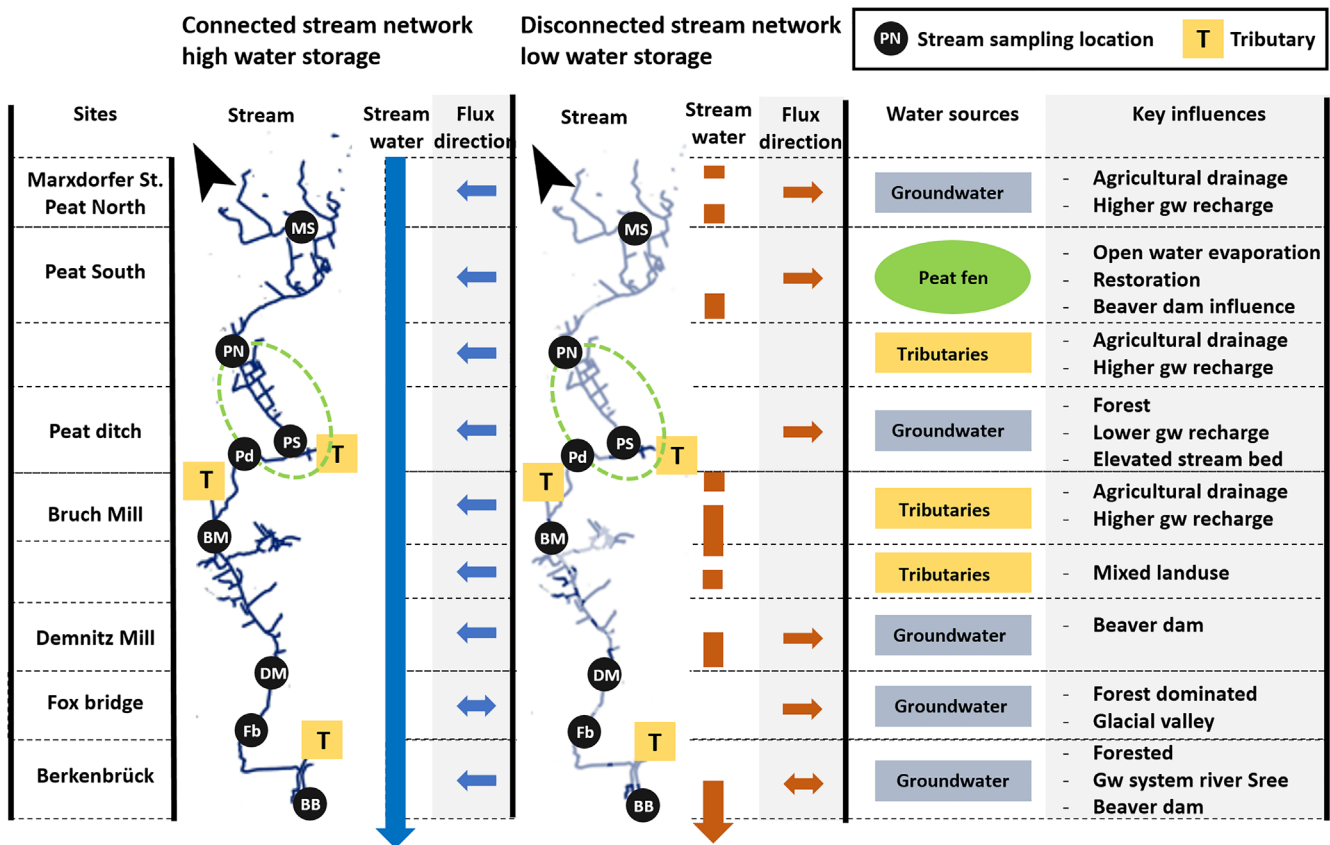

FIGURE 8 Conceptional model of the connected (left) and disconnected (centre) DMC stream network with main related influences (right)

connectivity and the value of spatial sampling to understand hydrological function: While the locations upstream of the peat fen showed little influence of open water evaporation on the stream lc-excess, the peat fen with had areas of open water (e.g., beaver dams) and stronger potential for evaporation, especially during summer. These were hotspots for fractionation influencing the isotopic signatures in the stream water downstream, especially during low flow periods with longer water residence times in the peat fen. Therefore, stream water age estimates need to recognize the potential impacts of fractionation signals on resulting young water fractions or MTTs.

At Marxdorfer St. (1), groundwater influence was strong, which was reflected in low YWFs. Its location in the agricultural upper catchment and the small size (~3 km^2) of the subcatchment resulted in stream discharge in periods of high local groundwater storage draining in winter, and which ceased to flow during the growing season in late spring/early summer. At Peat North (2), the groundwater influence was also strong and reflected the larger and more complex sub-catchment and associated runoff generation processes. Discharge here also ceased in summer, but several weeks later than Marxdorfer St. (1). Water isotope signatures at Peat South (3) indicated evaporation during the spring and summer in the wetland. Water was present for a longer period at this site; but often not flowing as the water was impounded by a downstream beaver dam; which also affected the period of streamflow at the location Peat ditch (4). Downstream of the wetlands at Bruch Mill (5), water also flowed for longer periods as another tributary draining the NW of the DMC contributed groundwater from agricultural areas leading to a less pronounced evaporation signal. At Demnitz Mill (6), more agricultural land use fringes the channel, but other tributaries from adjacent forest areas east of the stream influenced this site. Furthermore, a beaver dam directly upstream of the sampling location resulted again in ponded water, with an evaporation signal when streamflow was stagnant. Even when flowing, surface water only reached the downstream Fox bridge (7) site in the wettest conditions. This part of the stream was a "losing reach" with stream water leakage to groundwater throughout the study period indicating another important subsurface storage deficit that was not refilled during rewetting periods. The year-round re-emergence of streamflow at Berkenbrück (8) and the low YWF (6.5%) indicate a strong dominance of groundwater during dry periods at the catchment outlet, which is consistent with the distinct hydrochemistry at this site (Smith, Tetzlaff, Gelbrecht, et al., 2020). This sampling location also experienced extensive beaver activity up and downstream of the sampling site. Further influences by the larger groundwater system of the nearby river Spree are likely (Smith, Tetzlaff, Gelbrecht, et al., 2020).

These observed patterns in surface and subsurface hydrological processes illustrate the importance of land use and landscape management (drainage, forestry, restoration, beavers etc.) on spatial dynamics of surface water availability, stream connectivity and modification of the seasonal tracer signal (e.g., YWF) in such lowland landscapes. Catchment-specific patterns of river network disconnection are becoming more widely investigated in contrasting environments and have been related to climate change-induced water balance

alterations, very localized site characteristics (e.g., in the steep, forested Pacific Northwest; Ward et al., 2020), and landscape structure (Bertrand et al., 2012). More explicit, an assessment of the role of land use and vegetation age classes (Germer et al., 2011) on groundwater recharge and spatial connectivity patterns could be usefully integrated into further analysis through spatially distributed hydrological modelling (Holman et al., 2017).

The effects of the peat fen on the downstream nutrient dynamics are being assessed in on-going work at DMC and again, isotopes have given invaluable insights into hydrological function (cf. Smith et al., 2020b). Key questions revolve around the way in which runoff derived from groundwater draining the agricultural areas interacts with the organic-rich wetland soils, with slower flows, ponded water and longer residence times, in potentially warmer conditions (Lam et al., 2011). Such changes are likely to affect biogeochemical processes (Stieglitz et al., 2003), riparian vegetation (Pettit & Froend, 2018), as well as local groundwater recharge (Krause et al., 2007), and resulting runoff generation (and associated isotope composition) especially during drought conditions. Reactive tracers would therefore also give additional insight (Li et al., 2020) on in-stream biogeochemical processes (Dieter et al., 2011). In the lower catchment, the effects of land use, especially forest cover and age classes (Germer et al., 2011), as well as riparian management, also need to be considered to fully understand potential climate change impacts (Holman et al., 2017; Natkhin et al., 2012). Future surface connectivity patterns under climate change will have implications for in-stream biogeochemical processes (Dieter et al., 2011), water ages (Soulsby et al., 2015), and aquatic habitats (Sarremejane et al., 2017). Catchment scale understanding from isotope studies as provided here can help identify the dominant hotspots for process-based research and climate mitigation.

Most importantly, in our study, vegetation cover emerged as the key land management focus for sustainable water management because of the groundwater recharge implications of forest cover (Natkhin et al., 2012) and the local importance of green water fluxes (Smith, Tetzlaff, Gelbrecht, et al., 2020; Smith et al., 2020b). The use of soil water or groundwater as a transpiration source shows dependency on tree species, age, stand density and distribution (Song et al., 2016), with a tendency for deeper water sources in more arid climates (Evaristo & McDonnell, 2017). Potential impacts of pine plantations (i.e., uniform age distributions in stems) on the regional groundwater levels have been also highlighted by Nützmann et al. (2011) and evidence-based assessment of water footprints of different land use will be essential in studying and managing local subsurface and surface water resources (Neill et al., 2021).

5.3 | In-stream processes and water ages

Our study further identified hotspots for in-stream evaporation and the downstream transmission of fractionation signals, especially under low flows. Isotopic fractionation of the groundwater-dominated streamflow occurred in peatlands and sites affected by beaver dams,
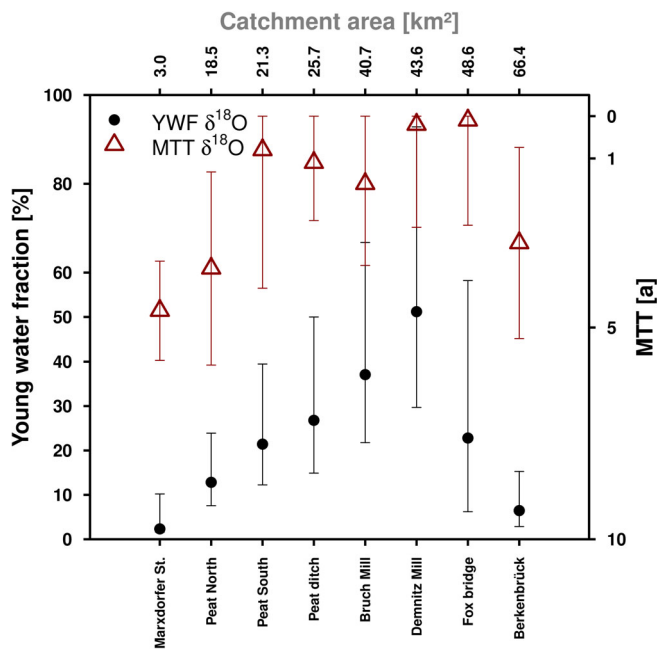
FIGURE 9 Tentative young water fraction and MTT estimations and conservative uncertainties for the DMC stream sampling sites

similar to findings by Sprenger, Tetzlaff and Soulsby (2017) for a peatland in Scotland. In this context, analysis of the YWF showed that caution is needed when applying this method in situations where tracer signals are modified due to evaporative fractionation which is not considered in YWF approach as noted by Kirchner (2016). The MTTs have similar limitations in terms of not considering evaporative fractionation effects (McGuire & McDonnell, 2006), but can also be more generally uncertain as metrics of hydrological function in heterogenous catchments (Kirchner, 2016).

As a result of these fractionation effects, some of the calculated MTTs were unrealistically low and YWFs too high, showing high uncertainties. However, despite these limitations, both methods captured and constrained well some of the differences among the sites (Figure 9) and the spatial aspects in streamflow generation. The domination of groundwater in discharge was apparent in the high MTT and low YWF at the two upstream sites (Marxdorfer St. (1), Peat North (2)). This is in line with findings from Smith et al. (2020a) and Massmann et al. (2009). Low YWFs (Figure 9) and high MTTs were further apparent at the catchment outlet Berkenbrück (8), indicating a higher groundwater influence. At the other sites, seasonality in fractionation likely led to overestimations of YWFs and underestimations of MTTs. Intuitively, the fractionation processes imprinted on the stream water isotopic signature by open water evaporation is highly dynamic in space and time (Sprenger et al., 2017).

6 | CONCLUSION

Water stable isotopes were used to supplement existing data in a long-term research catchment to enhance our understanding of

ecohydrological function and catchment-scale connectivity. Our sampling over 2 years coincidentally captured catchment responses to drought conditions. Water isotope signatures enabled us to assess the spatial variations of ecohydrological partitioning between blue and green water fluxes in the DMC that are likely to become more marked under climate change predictions. Isotope dynamics provided some preliminary assessment of stream water ages through estimations of young water fractions and MTTs, which will be more constrained by ongoing monitoring. We also assessed land management and vegetation impacts on blue water fluxes. We found that forested areas are more likely to reduce groundwater recharge under water stress, causing a faster decline of groundwater levels. These patterns are likely to emerge in similar landscapes under climate change conditions and adaptation or extension of observation networks in long-term research catchments may be needed to accommodate such emerging new research foci. Longevity of the ongoing drought impact on the landscape hydrology (reduced soil water storage, disconnected stream networks, reduced surface waters) and the direct consequences for dependent ecosystem services were striking.

Climate change, land use characteristics and anthropogenic impacts on hydrological partitioning all have the potential to increase pressure on water resources and ecosystem services in drought-sensitive lowland areas like the DMC. Future land and water management challenges will revolve around balancing the seasonality of plant-available water with maintaining groundwater recharge and streamflow. Our results highlight the complexity of the trade-offs between blue and green water partitioning in lowlands with limited soil water storage under dry conditions, the resulting spatial patterns of ecohydrological processes and connectivity as well as the need for consideration of partitioning and spatial patterns in addressing local management objectives. Improved ecohydrological understanding in complex lowland headwaters provides an important evidence base for stakeholders and management and a platform for monitoring the effects of potential management options. Future work will require close collaboration with local actors in agriculture, forestry, nature conservation, and interdisciplinary research efforts to underline the wider societal benefits of long-term catchment studies.

DATA AVAILABILITY STATEMENT

The data are available from the corresponding author upon reasonable request.

ORCID

Lukas Kleine https://orcid.org/0000-0001-9516-7628
Doerthe Tetzlaff https://orcid.org/0000-0002-7183-8674
Aaron Smith https://orcid.org/0000-0002-2763-1182
Tobias Goldhammer https://orcid.org/0000-0001-8897-4659
Chris Soulsby https://orcid.org/0000-0001-6910-2118

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