Integrated ecohydrological hydrometric and stable water isotope data of a drought-sensitive mixed land use lowland catchment

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Abstract

Data from long-term experimental catchments are the foundation of hydrological sciences and are crucial to benchmark process understanding, observe trends and natural cycles, and are prerequisites for testing predictive models. Integrated data sets which capture all compartments of our landscapes are particularly important in times of land use and climate change. Here, we present ecohydrological data measured at multiple spatial scales which allows differentiation of "blue" water fluxes (which maintain streamflow generation and groundwater recharge) and "green" water fluxes (which sustain vegetation growth). There are two particular unique aspects to this data set : a) we measured water stable isotopes in the different landscape compartments (that is in precipitation, surface water, soil, ground- and plant water); and b) we conducted this monitoring during the extreme drought of 2018 in Central Europe. Stable water isotopes are so useful in hydrology as they provide "fingerprints" of the pathways water took when moving through a catchment. Thus, isotopes allow to evaluate the dynamic relationships between water storage changes and fluxes, which is fundamental to understanding how catchments respond to hydroclimate perturbations or abrupt land use conversion. Second, as we provide the data until 2020 one can also investigate recovery of water stores and fluxes after extreme droughts. Last but not least: lowland headwaters are often understudied systems despite them providing important ecosystem services such as groundwater and drinking water provision and management for forestry and agriculture. All data presented in this paper are available from the IGB open data repository FRED with detailed metadata (https://doi.org/10.18728/igb-fred-813.1; Tetzlaff et al., 2023).

1. Introduction

Progress in scientific hydrology and provision of an evidence base for sustainable land and water management are only possible due to detailed, long-term observational data collected from experimental watersheds (Hewlett et al., 1969; Robinson et al., 2013). Such experimental "outdoor laboratories" are invaluable scientific resources given the complexity of increasing pressures on water supplies (e.g. Cosgrove and Loucks, 2015), land use change (Neill et al., 2021) and the uncertain effects and non-stationarity of projected climate change (Milly et al., 2015).

Ecohydrology adopts an interdisciplinary approach to investigate links between the structure and function of ecological systems and the partitioning, flux and storage of fresh water (Guswa et al., 2020). Recent advances in monitoring and modeling have created manifold opportunities to address urgent ecohydrological questions on the importance of links between processes across the critical zone (CZ) - the dynamic, life-sustaining near-surface of the terrestrial earth that extends between the top of vegetation canopies, through the soil and into groundwater (Grant & Dietrich, 2017). Within the CZ concept, vegetation plays a central and dynamic role in partitioning incoming precipitation into "blue water" fluxes (streamflow generation and groundwater recharge) and "green water" fluxes which maintain vegetation growth (Evaristo et al., 2015).

To enhance ecohydrological process understanding in catchment systems, robust, multi-scale integrated data sets are required (Tetzlaff et al., 2021). In this regard, water stable isotopes and other tracers can help identify sources and pathways of water in the landscape and across the CZ to elucidate how different land use affects water partitioning between green and blue water fluxes (Dubbert and Werner, 2019; Tetzlaff et al., 2015). Importantly, water stable isotopes have enhanced the characterization of the celerity of hydrological fluxes in different CZ compartments, as well as quantifying the velocity of water particles and associated mixing relationships in the subsurface (Benettin et al., 2015; Birkel et al., 2011). Evaluating the dynamic relationships between water storage changes and fluxes is fundamental to understanding how catchments respond to hydroclimate perturbations, such as anomalous dry or wet periods, or abrupt land use conversion. This provides a more nuanced and integrated understanding of how key ecohydrological couplings may be at risk during long-term changes in blue and green water partitioning resulting from climate and land use change (Orth and Destouni, 2018). Such integrated understanding is important in the context of projected increases in air temperature, aridity, and in precipitation patterns, which may cause more variability in water availability threatening the sustainability of important ecosystem services (Okruszko et al., 2011). As an increase in drought frequency and severity is expected across Europe as the 21st century progresses, the development of effective and evidence-based amelioration measures to underpin sustainable and integrated land and water management policies for changing climatic conditions is urgently needed (Samaniego et al., 2018).

Consequently, integrated ecohydrological and stable isotope data sets targeted at understanding the effects of different types of environmental change have outstanding potential, not least because interdisciplinary environmental research tends to give unanticipated insights (Burt, 1994). Such integrated data streams allow identification and quantification of the linkages between rainfall, soil moisture, groundwater and runoff generation, facilitating deeper understanding of flood and drought risk in different types of landscapes and under different land use management (Huntingford et al., 2014).

Water resources in the extensive, glacially formed, lowland landscape of northern Europe, including the North German Plain sustain food production (Gutzler et al., 2015; Barkmann et al., 2017) and water supplies to large cities like Berlin. Interestingly, such lowland catchments are still relatively understudied compared to more upland headwater landscapes with stronger topographic controls on drainage of surface and subsurface water (Devito et al., 2005). In low elevation catchments across the North German Plain, streams are usually groundwater-dominated, but the temporal and spatial heterogeneities in the hydrological functioning of these catchments are still not fully understood (Boulton and Hancock, 2006). For example, there is still a limited evidence base for quantifying how drought affects groundwater recharge and stream flow generation in lowland areas in Central Europe, including the cessation of flow during the summer (Germer et al., 2011).

To help address these knowledge gaps, here, we present a comprehensive set of ecohydrological hydrometric and stable water isotope data of two years for the Demnitzer Mill Creek catchment, Northeast Germany. The data set is unique in its integrative characteristics; that the different compartments of the CZ were sampled across a mesoscale catchment in terms of their isotopic signature and supporting ecohydrological data. By coincidence, these first two years, of what will be a long-term study, captured the changing impacts of a prolonged drought period (2018-2020) with a strong negative rainfall anomaly that became the most severe regional drought so far in the 21st century (Kleine et al., 2021a). The data allow the effects of droughts (and their persistence) on water storage, fluxes and age dynamics in the CZ to be investigated (Smith et al., 2022). Our objective here is to provide this high spatio-temporal resolution ecohydrological dataset to improve understanding of the storages and flow pathways of both blue and green water across processes at the larger catchment scale in lowland catchments. We are continuing these observations to assess long-term climatic trends at this drought sensitive region of Northeast Germany, which is characterized by high water losses due to evapotranspiration and poor water retention in the widespread sandy soils (Smith et al., 2021). Further, these data can potentially be used to understand the hydrologic functioning of other drought sensitive regions beyond northeast Germany.

2. Site description

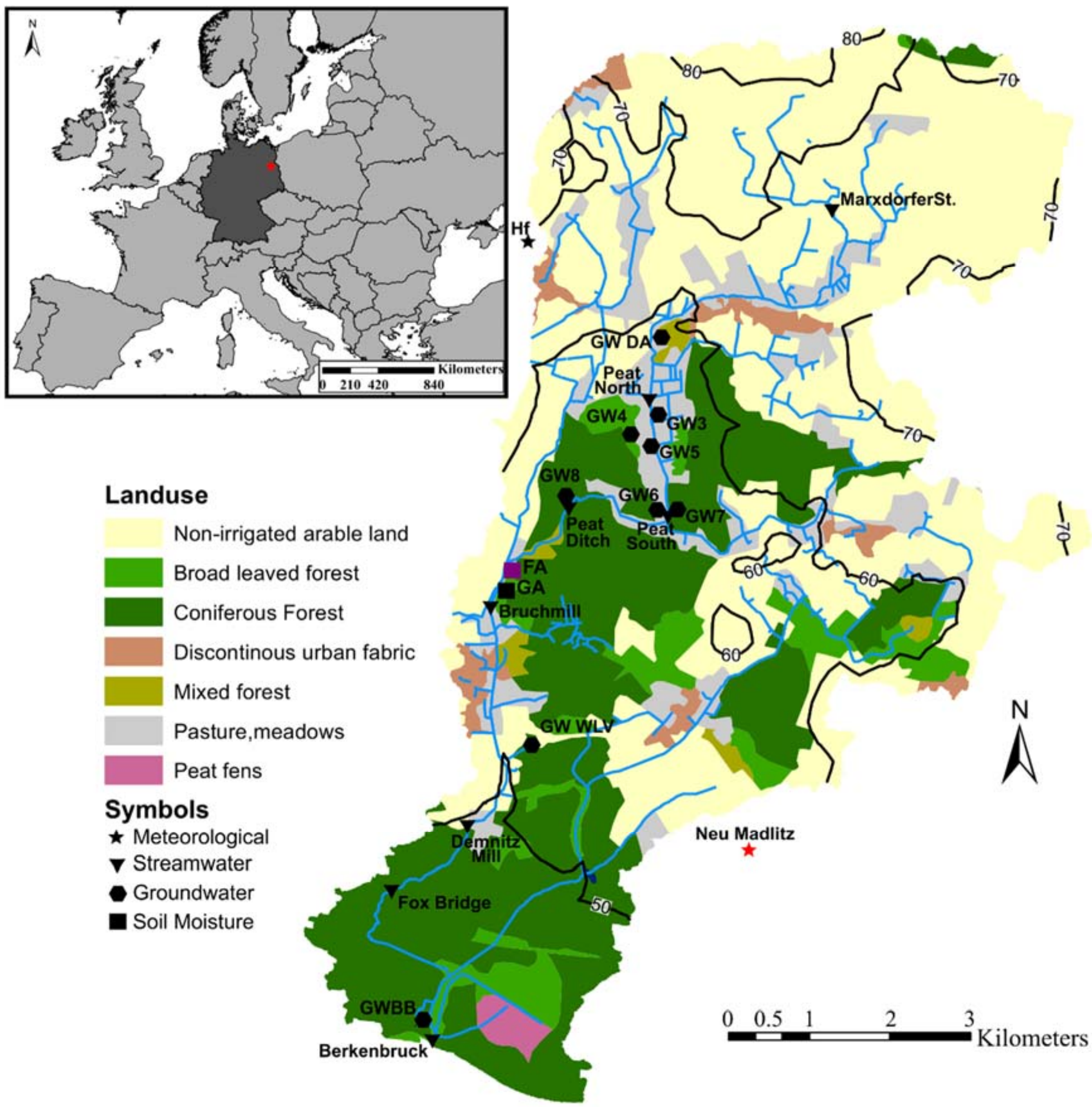

Figure 1: The Demnitzer Mill Creek catchment and its location within Europe and Germany. Measurement types are indicated in the legend, with red indicating no isotope measurements, black and purple indicating isotope measurements, and purple additionally indicating sap flow and sap isotope measurements. Meteorological measurements at Neu Madlitz were conducted by the German Weather service (DWD Deutscher Wetterdienst).)

Table 1 - Overview of the properties of the Demnitzer Millcreek catchment at the catchment outlet. Overview includes physiological characteristics, landuse, and geology.

Area (km2)	66.39	**Topographic Relief (m)**	50.23
Runoff Ratio	0.10	**Mean Slope (%)**	1.98
Landuse (%)		**Geology (%)**	
Mixed Forest	1.0	Base moraine	35.5
Conifer Forest	29.2	End moraine	2.3
Broadleaf Forest	6.0	Deposits of glacial valleys	6.9
Peat	0.7	Peat Fen	5.9
Pasture	10.2	Periglacial/fluvial deposits	16.3
Agricultural/arable land	50.4	Glacial/fluvial deposits	31.1
Urban	2.5	Sandy peat fen	2.0

The data presented here were monitored in the Demnitzer Millcreek catchment (DMC) located in NE Germany (52°23′N, 14°15′E; Figure 1). The DMC is a lowland drought-sensitive area south east of Berlin, the German capital, and situated in the North German Plain. The region has high socio-economic significance through the provision of numerous ecosystem services; including food security, timber production, groundwater recharge and river flow generation which sustains drinking water supplies for Berlin (Kleine et al., 2021a). The original motivation behind establishing DMC as an observatory in 1990 was to investigate the impact of agricultural pollutants on surface water quality (Gelbrecht et al., 2000, 2005).

The hydroclimate is temperate with warm, humid summers (Kottek et al., 2006). Mean annual precipitation and air temperature are 567 mm yr^{-1} and 9.6°C, respectively (DWD, 2020, for 2006-2015). Seasonal contrasts are characterized by higher summer precipitation, mainly from high intensity, convective events; and slightly lower precipitation during frequent, frontal rainfall events in winter. The landscape was shaped by the last glaciation (Weichselian); soils are predominantly sandy and formed on glacial and fluvial deposits (Kleine et al., 2021b). The catchment is dominated by groundwater and likely had little surface runoff before human intervention. Previously, numerous peat fens and freshwater lakes in hollows existed, but these were drained during a long history of anthropogenic management (Nützmann et al., 2011). Land use is currently dominated by farming and forestry (Kleine et al., 2020; Smith et al., 2020c). The catchment is also relatively sparsely populated, and has recently experienced recolonization of beaver (Smith et al., 2020a), wolf (Vogel, 2014) and even sporadic sighting of elk (Martin, 2014).

Maintenance of crucial ecosystem services in the landscape is dependent on sufficient seasonal precipitation input to sustain adequate soil moisture levels in the rooting zone to support crop and tree growth (Drastig et al., 2011); and acceptable groundwater recharge to sustain groundwater-surface water exchanges. However, high water losses due to evapotranspiration (~ 90 % of total precipitation), particularly from forested areas and poor water retention in the widespread sandy soils (Smith et al., 2021), result in catchment drought sensitivity (Kleine et al., 2020). Further, increased flow disconnections and fragmentation of the stream network occurs during droughts (Kleine et al., 2021a; Smith et al., 2021).

3. Data and instrumentation overview

3.1 Instrumentation overview

A fully automatic weather station (AWS) was installed and has been operated in Hasenfelde (Hf, Figure 1) since April 2018, including net radiation, air temperature, relative humidity, precipitation and ground heat flux every 15-minutes. ~~A modified autosampler (ISCO 3700, Teledyne Isco, Lincoln, USA) was installed nearby to collect daily samples of precipitation to supplement the AWS.~~ Weekly cumulative precipitation was additionally collected at four locations nested from north to south in the catchment: Marxdorfer St., Demnitz Mill, Bruchmill, and Berkenbruck (Figure 1&2) from July 2018 to April 2020. Throughfall was collected under the canopy at Forest A at five locations (Forest A1-5) within a 10 m square fenced area. Throughfall was collected using standard rain gauges (Rain gauge kit, S. Brannan & Sons, Cleator Moor, UK; https://doi.org/10.18728/igb-fred-813.1~~https://doi.org/10.18728/igb-fred-623.0~~)

Soil moisture and temperature profiles were established at Forest A (FA) and Grass A (GA) in June 2018 with 18 sensors per site (SMT-100, Umwelt-Geräte-Technik GmbH, Müncheberg, Germany). The sensors were distributed equally at soil depths of 20, 60, and 100cm at each site (i.e. three sensors per depth), measuring every 15-minutes (https://doi.org/10.18728/igb-fred-813.1~~https://doi.org/10.18728/igb-fred-623.0~~).

Sap flow measurements were established in 12 trees at Forest A including Scots Pine (*Pinus sylvestris*), European Oak (*Quercus robur*), common hazel (*Corylus avellana*), and Red Oak (*Quercus rubra*). Measurements were conducted using 2-4 radially installed thermal dissipation-based sap flow sensors (TDP probes, Dynamix Inc., Houston, TX, USA). Sap flow measurements were recorded every 15 minutes (https://doi.org/10.18728/igb-fred-813.1~~https://doi.org/10.18728/igb-fred-623.0~~). Sensors were installed at approximately 1.3 m above ground. The tree diameter was also measured at this height (DBH; mean: 76 cm; SD: 35 cm). All sensors consisted of two thermometers installed in the sapwood in 4 cm vertical distance from each other and were shielded from external sources of temperature change (e.g. radiation). The upper thermometer was heated and differences in temperature were collected hourly with a CR1000 data logger (Campbell Scientific, USA). The temperature difference was used to calculate flux velocity and combined with the sapwood area to calculate a flux rate. Conditions of zero transpiration were determined from daily maximum temperature differences. The resulting flux rate per unit sapwood area was adjusted to the plot using a ratio of sapwood area to forest area that was established with ten trees. More details can be found in Kleine et al., (2020).

Stream water level was established at four locations within the catchment; Peat North, Bruchmill, Demnitz Mill, and Berkenbruck (https://doi.org/10.18728/igb-fred-813.1~~https://doi.org/10.18728/igb-fred-623.0~~). Water level measurements were established by IGB Leibniz Institute of Freshwater Ecology and Inland Fisheries and recorded with divers ~~(Micro 10m and Baro)~~ at Peat North, ~~and~~ Demnitz Mill, and at Bruchmill ((Micro 10m and Baro divers, Van Essen Instruments). The divers utilized at each site include an internal atmospheric pressure correction ~~(AquiLite ATP 10, AquiTronic Umweltmeßtechnik GmbH, Kirchheim/Teck, Germany)~~.

Water level measurements began at Demnitz Mill in 1986, and in January and June 2018 for Peat North and Bruchmill, respectively. Water level has been recorded since 1982 at Berkenbruck using pressure transducers and was established and collected by the Landesamt fur Umwelt. Channel stability at Demnitz Mill and Berkenbruck has permitted rating curve development to translate water level measurements to discharge. ~~Daily stream water samples for stable water isotope analysis were also collected at Bruchmill from an autosampler (ISCO 3700, Teledyne Isco, Lincoln, USA), which was established in December 2018 (https://doi.org/10.18728/igb-fred-623.0).~~

Groundwater level divers were installed at five locations throughout the catchment in 2001 (GW3, GW4, GW5, GW7, and GW8) (Figure 1&2). Groundwater level at each site was measured every four hours with an AquiLite ATP-10 diver (AquiTronic Umweltmeßtechnik GmbH, Kirchheim/Teck, Germany) with internal correction for atmospheric pressure (https://doi.org/10.18728/igb-fred-813.1~~https://doi.org/10.18728/igb-fred-623.0~~).

3.2 Isotope sampling overview

A modified autosampler (ISCO 3700, Teledyne Isco, Lincoln, USA) was installed nearby the AWS to collect daily samples of precipitation for water stable isotope analysis.~~ to supplement the AWS.~~ Daily stream water samples for stable water isotope analysis were ~~also~~ collected at Bruchmill from an autosampler (ISCO 3700, Teledyne Isco, Lincoln, USA), which was established in December 2018 (https://doi.org/10.18728/igb-fred-813.1~~https://doi.org/10.18728/igb-fred-623.0~~).

Manual sampling from different locations and different water cycle / landscape compartments supplemented the autosamplers installed for precipitation at Hasenfelde and for stream water at Bruchmill. Samples were taken from the weekly cumulative precipitation and throughfall (Forest A) for each location (Figure 2). Further, monthly samples of soil water were taken at 6 depths (2.5, 7.5, 15, 30, 60, 90 cm) in triplicate for Forest A and Grass A. This was complemented by synoptic, spatially distributed sampling of the upper 30cm in 2019. Samples were placed in a sterile zip-lock bag (CB400-420siZ, Weber Packaging GmbH, Güglingen, Germany) and analyzed using the direct water vapour equilibrium method (Wassenaar et al., 2008). Weekly grab samples of stream water were taken at all nested stream water locations (eight locations; Fig 1.). Groundwater isotopes were sampled at six groundwater wells (GW3, GW8, GW DA, GW6, GW WLV, GW BB). Vegetation isotopic sampling was conducted by taking twig samples from different vegetation in Forest A and samples of the non-green stem of the grass at site Grass A. Vegetation samples were stored at -20^{o}C after sampling until analysis. Reference for all isotope samples is https://doi.org/10.18728/igb-fred-813.1~~https://doi.org/10.18728/igb-fred-623.0~~.

A layer of paraffin was added to the bottom of all autosampler containers to prevent evaporation and fractionation from collected water. Autosamplers are emptied each week. Collected weekly precipitation, throughfall, stream water, and groundwater were sealed and refrigerated until isotopic analysis (usually within one week).

All liquid water samples (isotopes in precipiptation P_{iso}, in throughfall THR_{iso}, in streamwater Q_{iso}, in groundwater GW_{iso}) were filtered (0.2 µm, cellulose acetate, Lab Logistics Group GmbH, Meckenheim, Germany) and cooled before being analyzed using Cavity Ring-Down Spectroscopy (CRDS, L2130-i, Picarro, Inc., CA, USA). Additionally, the CRDS was used for the analysis of soil water extracted via the direct liquid water equilibrium method. Vegetation samples were extracted in January 2020 using the cryogenic extraction method given in Dubbert et al. (2013, 2014) and analyzed with the CRDS. For all CRDS analysis, we used four standards for a linear correction function and standards of the International Atomic Energy Agency (IAEA) for calibration. After quality-checking and averaging multiple analyses for each sample, the results were expressed in δ-notation with Vienna Standard Mean Ocean Water (VSMOW). Analytical precision was 0.05 ‰ standard deviation (SD) for $\delta^{18}O$ and 0.14 ‰ SD for δD. To screen for interference from organics, the ChemCorrect Software (Picarro, Inc.) was applied and contaminated samples discarded. Liquid samples were injected six times and the first three injections discarded.

Table 2 – Overview of site locations in DMC, including site name, coordinates, data collected, start and end dates, and resolution. N/A indicates not applicable, P is precipitation, GW is groundwater level, THR is throughfall, Ts is soil temperature, va is wind speed/direction, Ta is air temperature, Pa is air pressure, RH is relative humidity, NR is net radiation, Sap is sap flow, and subscript iso indicates isotopic sampling. AWS indicates measurements of P, va, Ta, Pa, RH, and NR

Site Name	ID	Location (UTM 33N)		Data Type	Installation/Start Date	Discontinued/End Date	Resolution	
		Latitude	Longitude				Temporal	Spatial
Marxdorfer St.	Marxdorfer St.	5810076	449773	P	Jul 9, 2018	Jun 2, 2020	Weekly	N/A
				P_{iso}				
				Q_{iso}	Jan 10, 2018	N/A		
				T_s	Aug 16, 2019	Jul 11, 2020	15-min	5cm
Hasenfelde	Hf	5809705	446068	P	Mar 17, 2018	N/A	15-min	2m
				P_{iso}	Jul 12, 2018		Daily	N/A
				v_a	Mar 17, 2018		15-min	2m
				T_a				
				P_a				
				RH				
				NR				
				T_s	Aug 16, 2019	Jul 11, 2020		5cm
Groundwater DA	GW DA	5808335	447527	GW_{iso}	Apr 16, 2019	N/A	Monthly	N/A
Peat North	PN	5807703	447474	Q_{iso}	Jan 10, 2018		Weekly	
Groundwater 3	GW3	5807499	447582	GW	Jan 10, 2001		4-hour	
Groundwater Ringwall	GW4	5807247	447233	GW	Feb 22, 2001		4-hour	
				GW_{iso}	Sep 11, 2018		Monthly	
Groundwater 5	GW5	5807099	447490	GW	Jan 10, 2001		4-hour	
Peat Ditch	Peat Ditch	5806364	446487	Q_{iso}	Mar 21, 2018		Weekly	
Groundwater Peat Ditch	GW8	5806320	446488	GW	Jan 10, 2001		4-hour	
				GW_{iso}	Aug 15, 2018		Monthly	
Groundwater 7	GW7	5806307	447726	GW	Feb 22, 2001		4-hour	
Groundwater 6	GW6	5806274	447678	GW_{iso}	Sep 11, 2018		Monthly	
Peat South	Peat South	5806262	447712	Q_{iso}	Jan 10, 2018	N/A	Weekly	N/A
				T_s	Aug 16, 2019	Jul 11, 2020	15-min	5cm
Forest A	FA	5805520	445731	Sap	Apr 21, 2018	Nov 1, 2018	15-min	12 Trees
				SM	Jun 15, 2018	N/A		6 sites, 20, 60, 100cm depths

				SM_{iso}	Oct 18, 2018	Jul 16, 2019	Monthly	N/A
				THR	Jul 11, 2018	May 19, 2020	Weekly	5 sites
				THR_{iso}				
				T_s	Jun 15, 2018	N/A	15-min	6 sites, 20, 60, 100cm depths
Grass A	GA	5805125	445495	SM	Jun 15, 2018	Jan 7, 2020	15-min	6 sites, 20, 60, 100cm depths
				SM_{iso}	Oct 18, 2018	Jul 16, 2019	Monthly	N/A
				T_s	Jun 15, 2018	Jan 7, 2020	15-min	6 sites, 20, 60, 100cm depths
Bruchmill	Bruchmill	5805088	445459	P	Jul 9, 2018	Jun 2, 2020	Weekly	N/A
				P_{iso}				
				Q_{iso}	Jan 10, 2018 (weekly) Dec 28, 2018 (daily)	Dec 28, 2018 (weekly)	Weekly / Daily	
Groundwater WLV	GW WLV	5803322	445982	GW_{iso}	Sep 20, 2018	N/A	Monthly	
Demnitz Mill	Demnitz Mill	5802298	445188	P	Jul 9, 2018	Jun 2, 2020	Weekly	
				P_{iso}				
				Q	Feb 22, 2011	N/A	4-hour	
				Q_{iso}	Jan 10, 2018		Weekly	
Fox Bridge	Fox Bridge	5801469	444189	Q_{iso}	Jan 10, 2018	N/A	Weekly	
Groundwater Berkenbruck	GW BB	5799862	444611	GW_{iso}	Jan 21, 2019		Monthly	
Berkenbruck	Berkenbruck	5799604	444737	P	Jul 9, 2018	Jun 2, 2020	Weekly	N/A
				P_{iso}				
				Q	Nov 1, 1982	N/A	Daily	
				Q_{iso}	Jan 10, 2018		Weekly	
				T_s	Aug 16, 2019	Jul 11, 2020	15-min	5cm

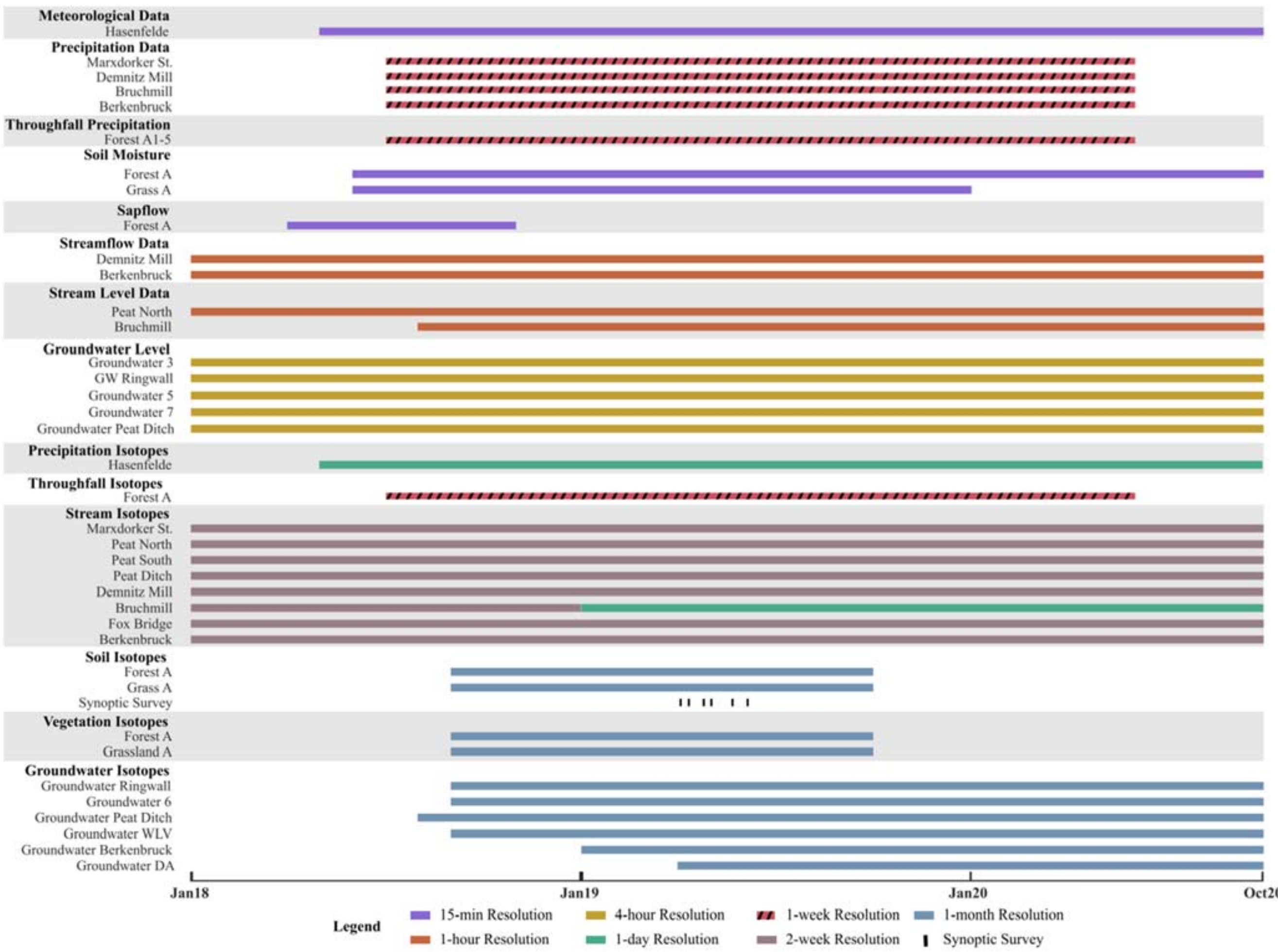

Figure 2: Measurement period for each parameter at each site and temporal resolution (colour code) of the measurements within the Demnitzer Millcreek Catchment including meteorological, soil, vegetation, stream, and groundwater hydrological and isotope data sets.

4. Precipitation and throughfall data

Monitoring for precipitation commenced in the 2018 summer drought when low rainfall inputs continued through the following winter (Figure 3a). Large rainfall events (>20 mm/d) were relatively rare and mostly summer convectional storms. Even by summer 2020, most months had below average rainfall. Throughfall at the Forest A site typically was 70-90 % of incident rainfall, with higher interception losses in low intensity summer storms and lowest in winter or high intensity summer storms. Heterogeneity in throughfall was marked (Figure 3b), emphasizing the importance of the forest canopy in redistributing net rainfall to the forest floor.

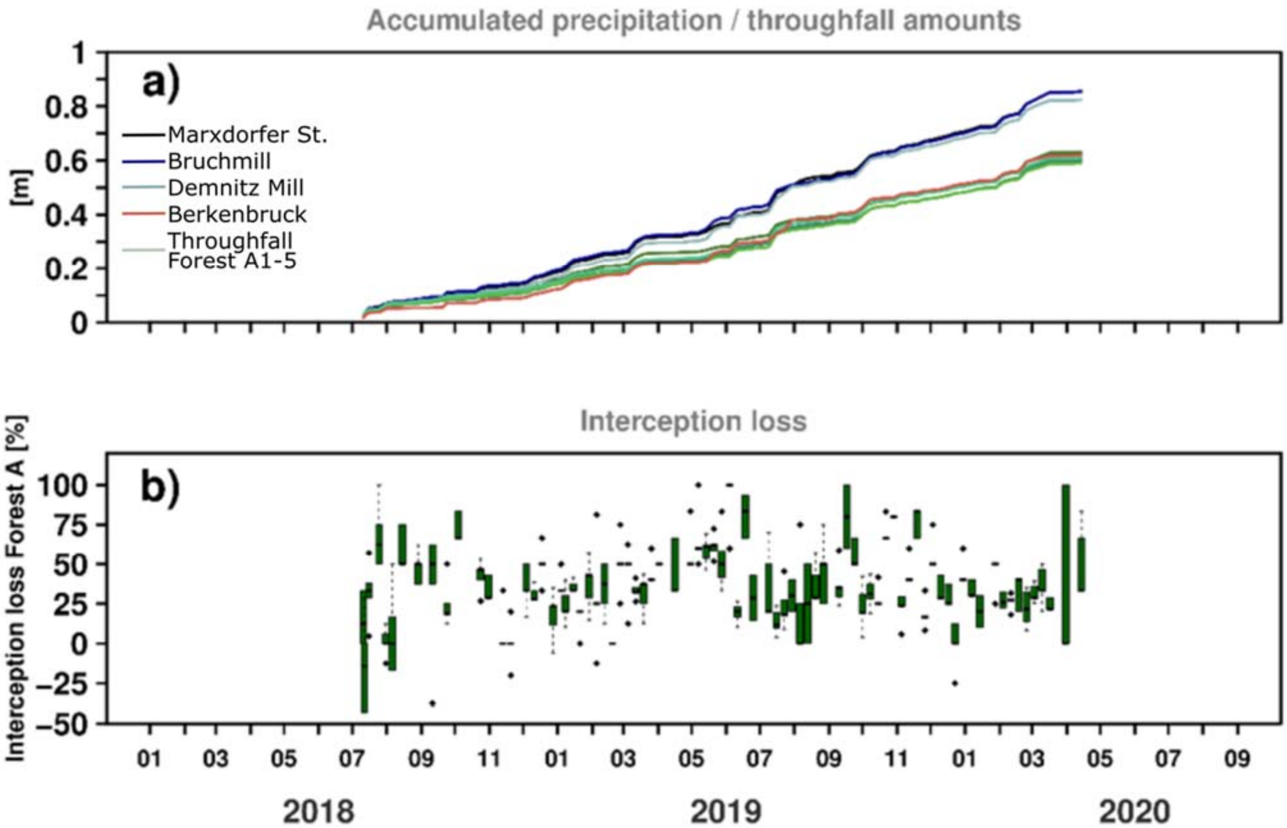

Figure 3: (a) Cumulative precipitation and throughfall at multiple locations throughout the catchment. Throughfall was collected weekly at Forest A with (b) five samplers (1-5) distributed throughout the 10m square fenced region. Precipitation at Bruchmill (nearby) was used as to calculate weekly interception loss.

5. Catchment hydrological data

Rainfall fluxes mostly drove short term soil moisture variations (Figure 4a, c); which were more responsive in the upper soil layers (at 20 cm) than deeper layers. There was higher variability in volumetric soil moisture under forested land cover, where soils are sandier, more structured and effective rainfall is lower due to interception losses. Seasonality in evapotranspiration (usefully indexed by sapflow in Figure 4b) modulated the effects of rainfall on soil moisture storage. Seasonal soil moisture dynamics also governed groundwater recharge and variation in groundwater levels, which had an annual range of ~1.5 m at well G3 and ~1m at the peat ditch well (Figure 4d). Despite clear winter recharge and spring drawdown in each well, peak winter and summer levels were lower in 2019 and still in 2020 despite a slight recovery compared to 2018 indicating the cumulative “memory effects” of the drought. This was also evident in the stream hydrograph with very low discharge peaks in 2019 and 2020, which also had prolonged periods where flow ceased in the summer, particularly at Berkenbruck. Thus, winter soil moisture replenishment was insufficient to match long-term groundwater recharge. These different correlations underline the added value of simultaneous data from long-term study sites on transpiration, soil water, groundwater and stream flow as droughts develop (Smith et al., 2022).

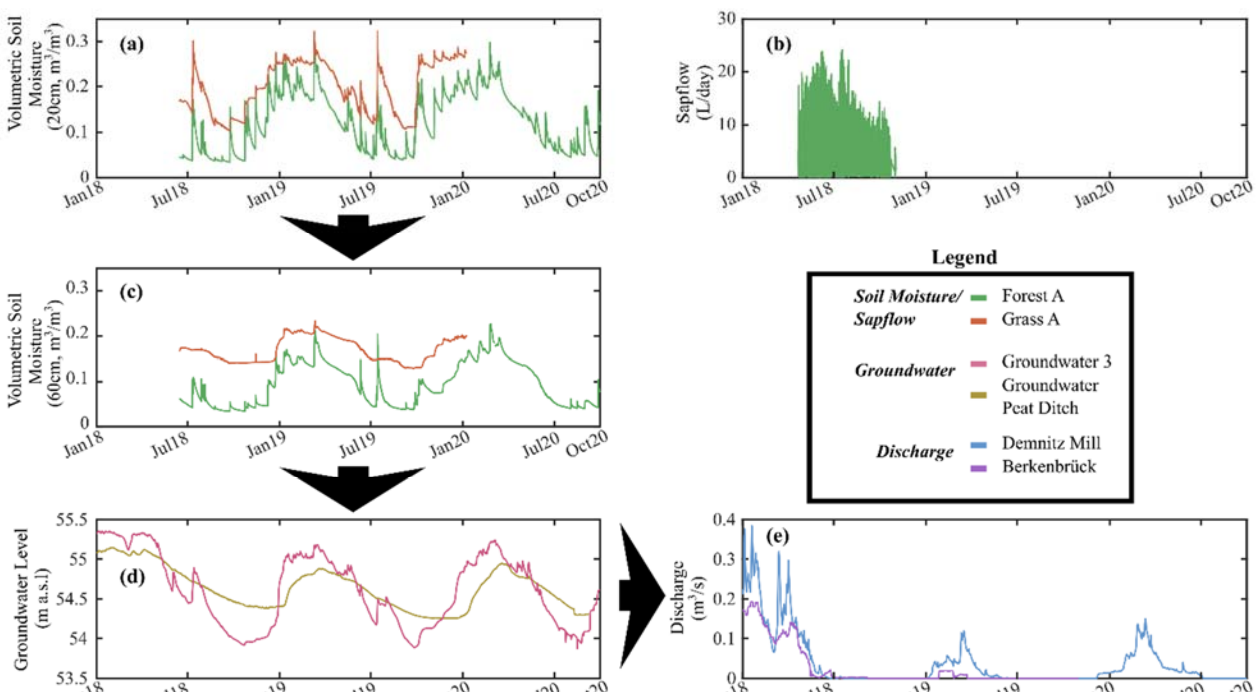

Figure 4: (a) Shallow soil moisture, (b) sapflow, (c) deep soil moisture, (d) groundwater levels and (e) discharge within the Demnitzer Millcreek catchment. Arrows show connections between layers and fluxes. *Groundwater 3 is within the wetland and Groundwater Peat Ditch is outside the wetland (near Forest A and Grass A, Fig. 1).

6. Stable water isotopes

Stable water isotope signatures in precipitation showed high day-to-day variability superimposed on strong seasonality; with more depleted values in winter and more enriched values in summer (Fig 5a). Interestingly, weekly throughfall signatures were very similar to the (weekly and daily) precipitation signal showing no strong signs of evaporative fractionation during canopy storage (Fig 5b). This likely reflects the high intensity nature of most summer rainfall, which affords limited opportunity for canopy evaporation. Streamwater signatures at all nested sites showed similar seasonality but much more damping in the signal (Fig. 5c). Groundwater was most damped, and similar in composition to streamflow during winter (Fig 5d). In summer, sites downstream of Marxdorfer Strasse showed evidence of evaporative fractionation from either the channel network or riparian soils and plotted below the meteoric water line before stream flow ceased. Monthly soil water samples showed higher variability in isotopic composition under forest than under grass, mainly reflecting soil characteristics with more retentive, loamy and wetter soils at the grassland site buffering the effects of rainfall inputs. At both sites, seasonal variation in isotopic composition tracked precipitation, though in deeper soil, the isotopic signal was more damped. Vegetation samples from the oaks showed higher variation than from grass.

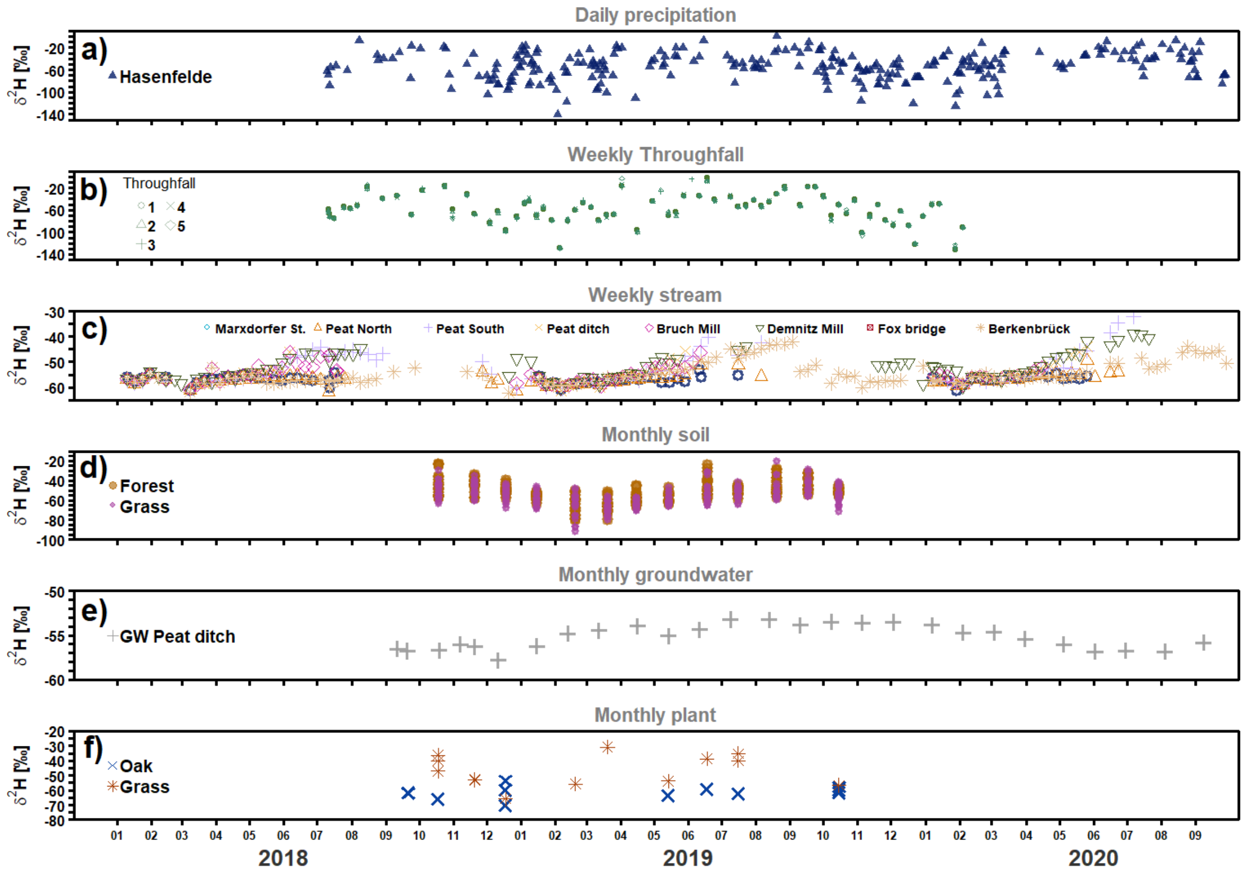

Figure 5: Time series of deuterium (δ^2H) in (a) precipitation, (b) throughfall (Forest A), (c) stream water, (d) soil water, (e) groundwater and (f) plant samples at various locations in the catchment.

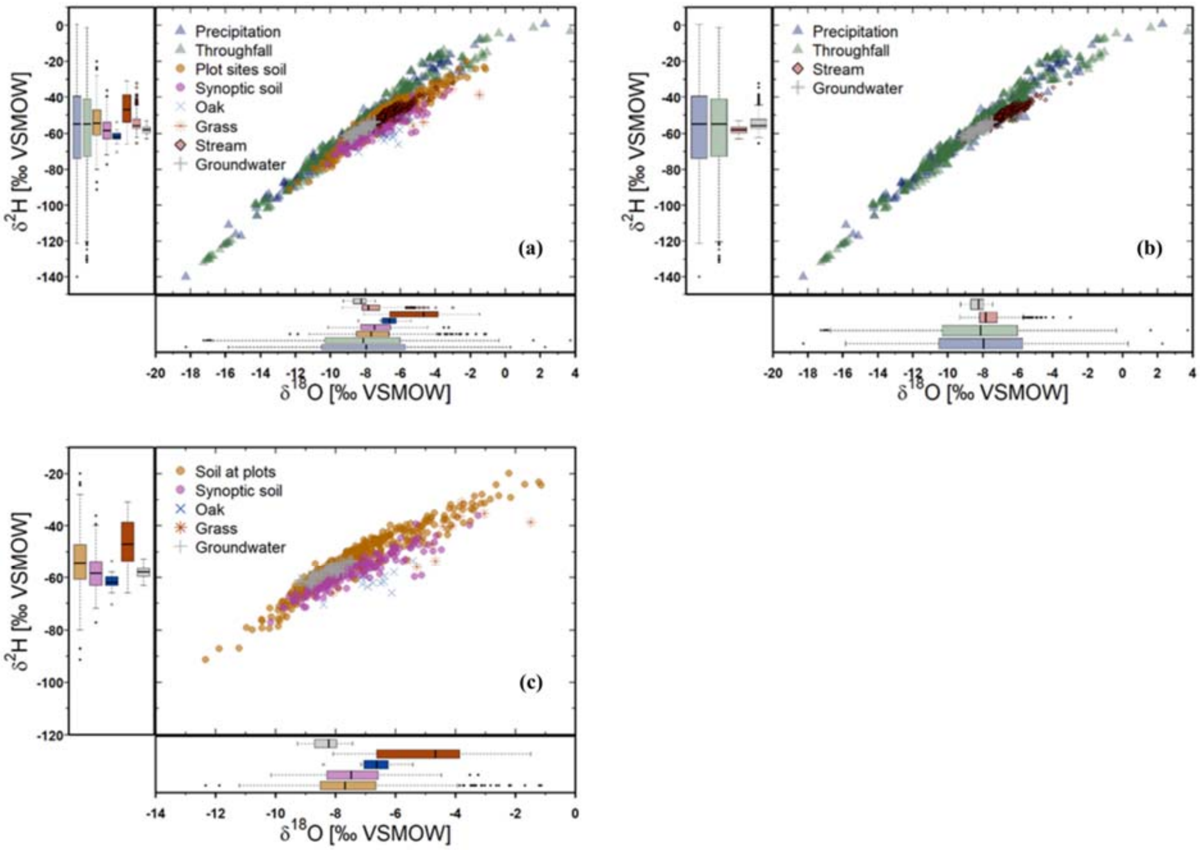

Figure 6: Dual isotope space (δ^2H-$\delta^{18}O$) plots for (a) all measured isotopic datasets, (b) precipitation, throughfall, stream, and groundwater, and (c) soil (multiple depths), synoptic soil survey (upper 30cm), vegetation, and groundwater.

Differences in the isotope dynamics of different critical zone compartments are shown in dual isotope space in Figure 6a. The damping of precipitation in groundwater and streamflow is apparent, as is the fractionation of more enriched summer stream flow samples (Figure 6b). The role of the soil in partitioning water is apparent from the overlap between deeper soil horizons and groundwater which were both more weighted to winter precipitation – when recharge is greatest (Fig 6c). Xylem water in oaks and grass tended to show the effects of fractionation, which was most marked in the oaks and may point to different soil water sources of root uptake.

7. Data availability

All data presented in this paper are available from the IGB open data repository FRED with detailed metadata ~~https://fred.igb-berlin.de/data/package/622 (Tetzlaff et al., 2022). The data are published with detailed metadata~~ (https://doi.org/10.18728/igb-fred-813.1; Tetzlaff et al., 2023 ~~https://doi.org/10.18728/igb-fred-623.0~~) and contact information for any further questions. There is a readme section per each dataset. We also included a digital elevation model, shapefile of the catchment boundary and the station locations.

8. Summary

The integrated data set presented in this paper is unique because: (1) it captures complicated ecohydrological dynamics over two years during an exceptional drought (in 2018/2019) in Central Europe; (2) the different compartments of the critical zone were monitored through stable water isotope data and complimentary ecohydrological data for contrasting land use and (3) multi-scale, nested catchment time series were derived. In total data from 49 time series / data sets are available. The data are quality controlled. We included meteorological data and precipitation and throughfall amount. Catchment response data include stream discharge at the catchment outlet and another nested site, and stream level data at two further sites; soil moisture from multiple depths at two locations (two different landuses), groundwater level data at five locations and sapflow measurements from one forest location. Stable water isotope data include precipitation water, throughfall, streamwater at eight sites, soil water isotopes from two sites plus spatially distributed samples of upper soils, vegetation samples at two locations and groundwater at six locations. Data continue to be collected and updated data sets will be published based on available resources.

As such, these data provide an excellent, integrated ecohydrological perspective on the drought response of a lowland agricultural landscape. Such data are of course important in their own right, but are equally invaluable for challenging environmental models as constraints on internal model function that can be used to increase confidence in the use of models in projecting the impacts of future change. Integrated data like the ones summarised here are also important for a range of scientific questions that are growing in importance as the effects of climate change become more apparent. These include understanding how do droughts develop and propagate through components of hydrological systems and compartments of the critical zone? What are the effects of land cover on this propagation and how does it affect water cycling in vegetation? How long does recovery of different system components take once rainfall anomalies become positive? How resilient are different critical zone compartments or entire landscapes against climate extremes such as droughts? Hopefully, this data set will be used by scientists to increase understanding on critical issues such as what are the water footprints of alternative land uses and how can these be reduced whilst maintaining societal needs. This will help to contribute to the development of more sustainable and resilient land and water management policies that will be needed in the face of increased longevity and frequency of droughts.

Author contributions: AS and LK prepared the data sets. Datasets were collected by LK and JF. Isotope data were analysed by DD. DT, CS, AS prepared the manuscript with contributions from all co-authors.

Competing interests: The authors declare that they have no conflict of interest.

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References:

Barkmann, T., Siebert, R., & Lange, A. (2017). Land-use experts’ perception of regional climate change: An empirical analysis from the North German Plain. *Climatic Change*, *144*(2), 287–301. https://doi.org/10.1007/s10584-017-2041-x

Benettin, P., Bailey, S. W., Campbell, J. L., Green, M. B., Rinaldo, A., Likens, G. E., McGuire, K. J., & Botter, G. (2015). Linking water age and solute dynamics in streamflow at the Hubbard Brook Experimental Forest, NH, USA. *Water Resources Research*, *51*(11), 9256–9272. https://doi.org/10.1002/2015WR017552

Birkel, C., Tetzlaff, D., Dunn, S. M., & Soulsby, C. (2011). Using lumped conceptual rainfall–runoff models to simulate daily isotope variability with fractionation in a nested mesoscale catchment. *Advances in Water Resources*, *34*(3), 383–394. https://doi.org/10.1016/j.advwatres.2010.12.006

Boulton, A. J., Hancock, P. J., Boulton, A. J., & Hancock, P. J. (2006). Rivers as groundwater-dependent ecosystems: A review of degrees of dependency, riverine processes and management implications. *Australian Journal of Botany*, *54*(2), 133–144. https://doi.org/10.1071/BT05074

Burt, T. P. (1994). Long-term study of the natural environment—Perceptive science or mindless monitoring? *Progress in Physical Geography: Earth and Environment*, *18*(4), 475–496. https://doi.org/10.1177/030913339401800401

Cosgrove, W. J., & Loucks, D. P. (2015). Water management: Current and future challenges and research directions. *Water Resources Research*, *51*(6), 4823–4839. https://doi.org/10.1002/2014WR016869

Devito, K., Creed, I., Gan, T., Mendoza, C., Petrone, R., Silins, U., & Smerdon, B. (2005). A framework for broad-scale classification of hydrologic response units on the Boreal Plain: Is topography the last thing to consider? *Hydrological Processes*, *19*(8), 1705–1714. https://doi.org/10.1002/hyp.5881

Drastig, K., Prochnow, A., Baumecker, M., Berg, W., & Brunsch, R. (2011). Agricultural Water Management in Brandenburg. *DIE ERDE – Journal of the Geographical Society of Berlin*, *142*(1–2), 119–140.

Dubbert, M., & Werner, C. (2019). Water fluxes mediated by vegetation: Emerging isotopic insights at the soil and atmosphere interfaces. *New Phytologist*, *221*(4), 1754–1763. https://doi.org/10.1111/nph.15547

Evaristo, J., Jasechko, S., & McDonnell, J. J. (2015). Global separation of plant transpiration from groundwater and streamflow. *Nature*, *525*(7567), 91–94. https://doi.org/10.1038/nature14983

Gelbrecht, J., Driescher, E., & Exner, H. J. (2000). Long-term investigations on nutrient input from catchment of the brook Demnitzer Mühlenfließ and restoration measures to reduce nonpoint pollution. In *Berichte des IGB* (Vol. 10, pp. 151–160). Institute Freshwater Ecology and Inland Fisheries. http://www.mendeley.com/documents/?uuid=e2bdb786-9532-4313-9dfb-17bc6f2c8e76

Gelbrecht, J., Lengsfeld, H., Pöthig, R., & Opitz, D. (2005). Temporal and spatial variation of phosphorus input, retention and loss in a small catchment of NE Germany. *Journal of Hydrology*, *304*(1), 151–165. https://doi.org/10.1016/j.jhydrol.2004.07.028

Germer, S., Kaiser, K., Bens, O., & Hüttl, R. F. (2011). Water Balance Changes and Responses of Ecosystems and Society in the Berlin-Brandenburg Region – a Review. *DIE ERDE – Journal of the Geographical Society of Berlin*, *142*(1–2), 65–95.

Grant, G. E., & Dietrich, W. E. (2017). The frontier beneath our feet. *Water Resources Research*, *53*(4), 2605–2609. https://doi.org/10.1002/2017WR020835

Guswa, A. J., Tetzlaff, D., Selker, J. S., Carlyle-Moses, D. E., Boyer, E. W., Bruen, M., Cayuela, C., Creed, I. F., van de Giesen, N., Grasso, D., Hannah, D. M., Hudson, J. E., Hudson, S. A., Iida, S., Jackson, R. B., Katul, G. G., Kumagai, T., Llorens, P., Lopes Ribeiro, F., … Levia, D. F. (2020). Advancing ecohydrology in the 21st century: A convergence of opportunities. *Ecohydrology*, *13*(4), e2208. https://doi.org/10.1002/eco.2208

Gutzler, C., Helming, K., Balla, D., Dannowski, R., Deumlich, D., Glemnitz, M., Knierim, A., Mirschel, W., Nendel, C., Paul, C., Sieber, S., Stachow, U., Starick, A., Wieland, R., Wurbs, A., & Zander, P. (2015). Agricultural land use changes – a scenario-based sustainability impact assessment for Brandenburg, Germany. *Ecological Indicators*, *48*, 505–517. https://doi.org/10.1016/j.ecolind.2014.09.004

Hewlett, J. D., Lull, H. W., & Reinhart, K. G. (1969). In Defense of Experimental Watersheds. *Water Resources Research*, *5*(1), 306–316. https://doi.org/10.1029/WR005i001p00306

Huntingford, C., Marsh, T., Scaife, A. A., Kendon, E. J., Hannaford, J., Kay, A. L., Lockwood, M., Prudhomme, C., Reynard, N. S., Parry, S., Lowe, J. A., Screen, J. A., Ward, H. C., Roberts, M., Stott, P. A., Bell, V. A., Bailey, M., Jenkins, A., Legg, T., … Allen, M. R. (2014). Potential influences on the United Kingdom's floods of winter 2013/14. *Nature Climate Change*, *4*(9), 769–777. https://doi.org/10.1038/nclimate2314

Kleine, L., Tetzlaff, D., Smith, A., Wang, H., & Soulsby, C. (2020). Using water stable isotopes to understand evaporation, moisture stress, and re-wetting in catchment forest and grassland soils of the summer drought of 2018. *Hydrology and Earth System Sciences*, *24*(7), 3737–3752. https://doi.org/10.5194/hess-24-3737-2020

Kleine, L., Tetzlaff, D., Smith, A., Goldhammer, T., & Soulsby, C. (2021a). Using isotopes to understand landscape-scale connectivity in a groundwater-dominated, lowland catchment under drought conditions. *Hydrological Processes*, *35*(5), e14197. https://doi.org/10.1002/hyp.14197

Kleine L, Tetzlaff D, Smith A, Dubbert M, Soulsby C. (2021b) Modelling ecohydrological feedbacks in forest and grassland plots under a prolonged drought anomaly in central Europe 2018-2020. *Hydrological Processes,* https://doi.org/10.1002/hyp.14325

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger Climate Classification Updated. *Meteorologische Zeitschrift*, *15*, 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Martin, I. (2014). Zum Vorkommen von Elchen (Alces alces) in Brandenburg. *Nationalpark-Jahrbuch Unteres Odertal*, *11*, 73–78.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., Stouffer, R. J., Dettinger, M. D., & Krysanova, V. (2015). On Critiques of "Stationarity is Dead: Whither Water Management?" *Water Resources Research*, *51*(9), 7785–7789. https://doi.org/10.1002/2015WR017408

Neill AJ, Birkel C, Maneta MP, Tetzlaff D, Soulsby C. (2021) Structural changes to forests during regeneration affect water flux partitioning, water ages and hydrological connectivity: Insights from tracer-aided ecohydrological modeling. *Hydrology and Earth System Sciences (HESS)*. https://hess.copernicus.org/articles/25/4861/2021/

Nützmann, G., Wolter, C., Venohr, M., & Pusch, M. (2011). Historical Patterns of Anthropogenic Impacts on Freshwaters in the Berlin-Brandenburg Region. *DIE ERDE – Journal of the Geographical Society of Berlin*, *142*(1–2), 41–64.

Okruszko, T., Duel, H., Acreman, M., Grygoruk, M., Flörke, M., & Schneider, C. (2011). Broad-scale ecosystem services of European wetlands—Overview of the current situation and future perspectives under different climate and water management scenarios. *Hydrological Sciences Journal*, *56*(8), 1501–1517. https://doi.org/10.1080/02626667.2011.631188

Orth, R., & Destouni, G. (2018). Drought reduces blue-water fluxes more strongly than green-water fluxes in Europe. *Nature Communications*, *9*(1), 3602. https://doi.org/10.1038/s41467-018-06013-7

Robinson, M., J. C. Rodda, and J. V. Sutcliffe (2013), Long-term environmental monitoring in the UK: Origins and achievements of the Plynlimon catchment study, Trans. Inst. Br. Geogr., 38, 451–463, doi:10.1111/j.1475-5661.2012.00534

Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., Zink, M., Sheffield, J., Wood, E. F., & Marx, A. (2018). Anthropogenic warming exacerbates European soil moisture droughts. *Nature Climate Change*, *8*(5), 421–426. https://doi.org/10.1038/s41558-018-0138-5

Smith, A., Tetzlaff, D., Gelbrecht, J., Kleine, L., & Soulsby, C. (2020). Riparian wetland rehabilitation and beaver re-colonization impacts on hydrological processes and water quality in a lowland agricultural catchment. *Science of The Total Environment*, *699*, 134302. https://doi.org/10.1016/j.scitotenv.2019.134302

Smith, A., Tetzlaff, D., Kleine, L., Maneta, M. P., & Soulsby, C. (2020). Isotope-aided modelling of ecohydrologic fluxes and water ages under mixed land use in Central Europe: The 2018 drought and its recovery. *Hydrological Processes*, *34*(16), 3406–3425. https://doi.org/10.1002/hyp.13838

Smith, A., Tetzlaff, D., Kleine, L., Maneta, M., & Soulsby, C. (2021). Quantifying the effects of land use and model scale on water partitioning and water ages using tracer-aided ecohydrological models. *Hydrology and Earth System Sciences*, *25*(4), 2239–2259. https://doi.org/10.5194/hess-25-2239-2021

Smith AA, Tetzlaff D, Maneta M, Soulsby C. (2022) Critical zone response times and water age relationships under variable catchment wetness states: insights using a tracer-aided ecohydrological model**.** *Water Resources Research*, https://doi.org/10.1029/2021WR030584

Tetzlaff, D., Buttle, J., Carey, S. K., van Huijgevoort, M. H. J., Laudon, H., McNamara, J. P., Mitchell, C. P. J., Spence, C., Gabor, R. S., & Soulsby, C. (2015). A preliminary assessment of water partitioning and ecohydrological coupling in northern headwaters using stable isotopes and conceptual runoff models. *Hydrological Processes*, *29*(25), 5153–5173. https://doi.org/10.1002/hyp.10515

Tetzlaff, D., Buttle, J., Carey, S. K., Kohn, M. J., Laudon, H., McNamara, J. P., Smith, A., Sprenger, M., & Soulsby, C. (2021). Stable isotopes of water reveal differences in plant – soil water relationships across northern environments. *Hydrological Processes*, *35*(1), e14023. https://doi.org/10.1002/hyp.14023

Tetzlaff D, Smith A, Kleine L, Dubbert D, Freymueller J, Soulsby C. (20223) An integrated ecohydrological hydrometric and stable water isotope data set of a drought-sensitive mixed land use lowland catchment. https://doi.org/10.18728/igb-fred-813.1https://fred.igb-berlin.de/data/package/622.

Vogel, C. (2014). Der Wolf in Brandenburg – Leben mit einem Rückkehrer. *Nationalpark-Jahrbuch Unteres Odertal*, *11*, 54–58.