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Using large-scale tracer-aided models to constrain ecohydrological partitioning in complex, heavily managed lowland catchments

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Abstract

Tracer-aided modelling (TAM) enhances ecohydrological process understanding, as stable water isotopes ($\delta^{18}O$ and $\delta^{2}H$) can help constrain equifinality and provide complementary information beyond streamflow. Despite being primarily applied in rural (<100km2) catchments with minimal disturbance, TAM may assess epistemic uncertainties from unrecorded human activities affecting streamflow, improving model reliability. This study investigated four sub-catchments (Berste, Wudritz, Vetschauer, and Dobra) in the heavily-managed Middle Spree River basin (ca. 2800 km^2), in NE Germany, a strategically vital water resource supplying drinking water to Berlin, Germany's capital, and sustaining agricultural and industrial demands. Detailed evaluation of ecohydrological water partitioning in this evapotranspiration (ET)-dominated region is complicated by heterogeneous land use, extensive hydraulic infrastructure and overall intensive management. We used the spatially distributed tracer-aided model STARR to simulate the effects of natural water storage-flux dynamics and management interventions on streamflow over a 6-year period. Seasonal isotope data used for calibration additionally to streamflow effectively captured subsurface runoff, with isotope

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fractionation intensity strongly linked to ET apportionment. This multi-criteria calibration helped reduce equifinality in complex systems with human-induced epistemic challenges. Epistemic errors were manifested as strong trade-offs between the information content of the different calibration constraints (i.e., streamflow and isotopes). Although compromised solutions occasionally failed to meet acceptable performance thresholds for both calibrated variables, such conflicts highlight potentially important mismatches in process representation. Our modelling framework shows the potential for informative insights from wider use of (even sparse) isotope data sets in tracer-aided modelling of complex, heavily managed catchments.

Highlights:

1. **Seasonal isotopes disentangle runoff generation processes.**
2. **Ignoring minor evaporation in modelling biases ET partitioning.**
3. **Streamflow & isotope do not constrain spatial ET distribution.**
4. **Streamflow-isotope trade-offs indicate epistemic errors in observations.**
5. **Catchments without historical mining effects exhibit large groundwater discharge.**

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1. Introduction

Characterizing ecohydrological processes in sparsely monitored catchments with heterogeneous landscapes is inherently challenging due to spatially variable flow pathways and non-stationarity in climate inputs (Hrachowitz et al., 2013; McDonnell et al., 2007). This challenge can be even greater in catchments heavily modified by human activities, where a long and on-going history of disturbance can fundamentally alter processes and functioning (Marx et al., 2021). Distributed hydrological models are useful tools in addressing these challenges and are capable of capturing the dominant processes across spatio-temporal scales through regional parameterization (Fatichi et al., 2016). However, increasing model complexity to capture catchment heterogeneity makes it difficult to identify when models give "*the right answer for the wrong reason*" (Kirchner, 2006). In most catchments, rainfall and streamflow are the only available data for modelling. Streamflow-based calibration has therefore been the standard approach in hydrological modelling, leveraging the widespread availability of river discharge data to estimate model parameters across diverse catchments (Hrachowitz et al., 2013). However, calibration based on streamflow observations (single or multiple gauges) alone are usually insufficient to constrain hydrological model uncertainty, as certain parameters remain non-identifiable (Herrera et al., 2022). Consequently, simulations with multiple parameter sets can give equally plausible outputs, with equifinality being a pervasive issue in model applications (Beven, 2006). Multi-criteria calibration, that is, leveraging complementary datasets (e.g., soil moisture, ET, groundwater) in addition to streamflow, to mitigate this effect is increasingly common (Kuppel et al., 2018; Oliveira et al., 2021; Shah et al., 2021; Wu et al., 2023).

Stable water isotopes ($\delta^{18}O$, $\delta^{2}H$) are a potential solution that can help identify water sources, flow paths, and transit times, thus revealing process heterogeneity in catchments (Klaus and

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McDonnell, 2013; Sprenger et al., 2015). They are often used as complementary datasets to streamflow, offering additional insights into catchment hydrological behavior that can aid parametrization and modelling (Fenicia et al., 2008). In many cases, the integration of isotopes into models has advanced process representation, improving understandings of water partitioning and storage-flux interactions in heterogeneous landscapes (Birkel and Soulsby, 2015; Luo et al., 2024; McDonnell and Beven, 2014; Smith et al., 2022). Consequently, tracer-aided models (TAMs) have been increasingly applied worldwide (Jung et al., 2025). However, many TAM studies showed inevitable trade-offs in model performance resulting from conflicting information in the streamflow and isotopes data (Birkel et al., 2015; Scudeler et al., 2016; Wu et al., 2023). Such differences can highlight errors in model structure and inappropriate process conceptualization (Beven, 2006; McDonnell et al., 2007; Wu et al., 2025). This is sometimes inevitable, such as when unknown anthropogenic influences affect hydrological behaviour. For example, unregulated water abstractions and artificial drainage can alter streamflow patterns, but simulations may still reproduce observed discharge, even without parameterising human effects into models via overfitting, which can result in a misleading representation of the system. In addition, using some observations as “soft data” (i.e. qualitative information or measured data that are not used in calibration) to constrain models can alleviate some of the above issues (Efstratiadis et al., 2010; Wu et al., 2023). However, failing to rigorously evaluate trade-offs between isotopes and streamflow risks producing structurally biased results, even if models achieve seemingly acceptable objective metrics for both datasets. Explorations of how these trade-offs in multi-criteria modelling using isotopes to help better understand hydrological processes and indicating further improve models are relatively rare.

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Most TAMs focus on rural catchments (Soulsby et al., 2015) with limited anthropogenic disturbance (Yang et al., 2023), while complexities of ecohydrological processes are exacerbated in human-dominated systems where management measures can fundamentally alter hydrological connectivity and function (Wada et al., 2017). This creates critical unknowns in characterizing hydrological processes under anthropogenic alterations. In this regard, advancing tracer-aided methods to systematically evaluate hydrological dynamics at different spatial and temporal scales in heavily managed catchments can have advantages in modelling (Smith et al., 2021).

In this study, water stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) were used in a tracer-aided hydrological model (Spatially distributed Tracer-Aided Rainfall-Runoff, STARR), to help constrain estimates of ecohydrological partitioning and water balance compartments in four heavily modified sub-catchments of the Middle Spree catchment (MSC) in eastern Germany. These include the effects of agricultural irrigation, land use change, urbanisation and historic lignite mining with associated groundwater pumping. The area impacts a major national water resource as the Spree river forms Berlin's water supply and ongoing pressures and intensifying climate change have the potential to threaten future water provision and ecosystem stability (Arndt and Heiland, 2024). Despite this significance, quantitative evaluation of ecohydrological processes in the MSC is currently limited, as records of intensive water use are not always available, historic impacts are often undocumented and parameterising these human influences in hydrological models are difficult. Therefore, this study aims to provide a preliminary insight of ecohydrological couplings between storage and fluxes as well as effects on the partitioning into runoff generation processes and ET fluxes in parts of the MSC, with the following specific objectives addressed:

1. Assessing trade-offs between streamflow and isotope-aided constraints in calibration of

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ecohydrological modelling in intensively managed lowland catchments.

2. Quantifying the spatio-temporal dynamics of the water balance in intensively managed lowland catchments during wet and dry periods.
3. Examining how management activities can bias ecohydrological models and advancing isotope-aided methods to disentangle process dynamics in human-dominated systems.

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2 Materials and Methods

2.1 Study catchment

The Mid-Spree catchment (MSC) is located in the SE of Brandenburg, Germany (Figure 1). The 2806 km^2 sub-basin forms the middle part of the much larger Spree catchment (10105 km^2), accounting for 28.6% of the entire catchment area. Within the MSC, the Spree River flows from Cottbus to Beeskow and through the Spreewald UNESCO Biosphere Reserve, which is an extensive wetland area. Climate is sub-continental with low precipitation and hot and dry summers (Pusch et al., 2009). Mean annual precipitation in the headwaters of the entire Spree catchment range from 600mm to 1000mm, decreasing to 556 mm in the MSC, making it one of the driest regions in Germany. Average monthly temperatures range between 19.3°C in summer (June to August) and 1.9°C in winter (December to February), respectively. Annual potential evapotranspiration, based on the FAO-56 Penman-Monteith equation (Deutscher Wetterdienst (DWD), 2024), reaches 726mm, making the MSC water-limited and highly susceptible to climate change.

The topography is flat and 80% of MSC varies between 42 to 78 m.a.s.l, though the maximum elevation is 155.6 m.a.s.l. The course of Spree River through the MSC has a very low gradient (0.027 %).

We selected four gauged sub-catchments in the MSC: the river Berste (gauged at Bruckendorf), the Wudritz catchment (gauged at Ragow), the Vetschauer Mill Creek (gauged at Vetschau), and the Dobra catchment (gauged at Boblitz), in the southern tributaries of the Spree River as the main study catchments (Figure 1). They are mostly dominated by croplands (encompassing some of the most extensive areas in the MSC), with pasture and coniferous forests forming the

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other two major land uses in the four sub-catchments, accounting for 12-20% and 18-30% of the area, respectively.

The geology of the sub-catchments is dominated by fluvial and meltwater sediments, especially along the river reaches, while artificial fills (from mining spoil) constitute a major part in the Wudlitz and Dobra catchments, as a result of historic lignite extraction (Landesregierung Brandenburg, 2024). Sandy soils (58.7% of the area) and clay- sands (29.7%) dominate these sub-catchments, while peat soils are sporadically distributed.

The four sub-catchments, like much of the MSC, were influenced by intense lignite mining activities between 1960-1990 (Pusch and Hoffmann, 2000). Of our study sites, the Wudritz and Dobra catchments were most severely affected, though lakes and restored areas now occupy the former mining areas. These lakes are relatively small, shallow and linked to streamflow in an unknown and non-stationary way. Pumped mine water (sump water), from de-watering former open-cast mines in the Altdoberm, Schlabendorf and Seese regions was discharged to the southern tributaries of the Spree River. After the sharp decline in lignite production in the early 1990s, discharge volumes from southern tributaries in the MSC to the Spreewald are believed to be close to the pre-mining situation since 2018 (Landesregierung Brandenburg, 2024). However, more generally in the Spree catchment, the decline of pumped sump water volumes has been faster than the replenishment of the groundwater deficit, and the lowered groundwater table leads now to a high risk of lower river flows and water shortages in the MSC, and constitutes a threat to Berlin's water supply further downstream (Arndt and Heiland, 2024). At present, in these four sub-catchments, drinking water is extracted from groundwater wells, while authorised water withdrawals in channels for agriculture are limited to spring and summer months (Landesregierung Brandenburg, 2024).

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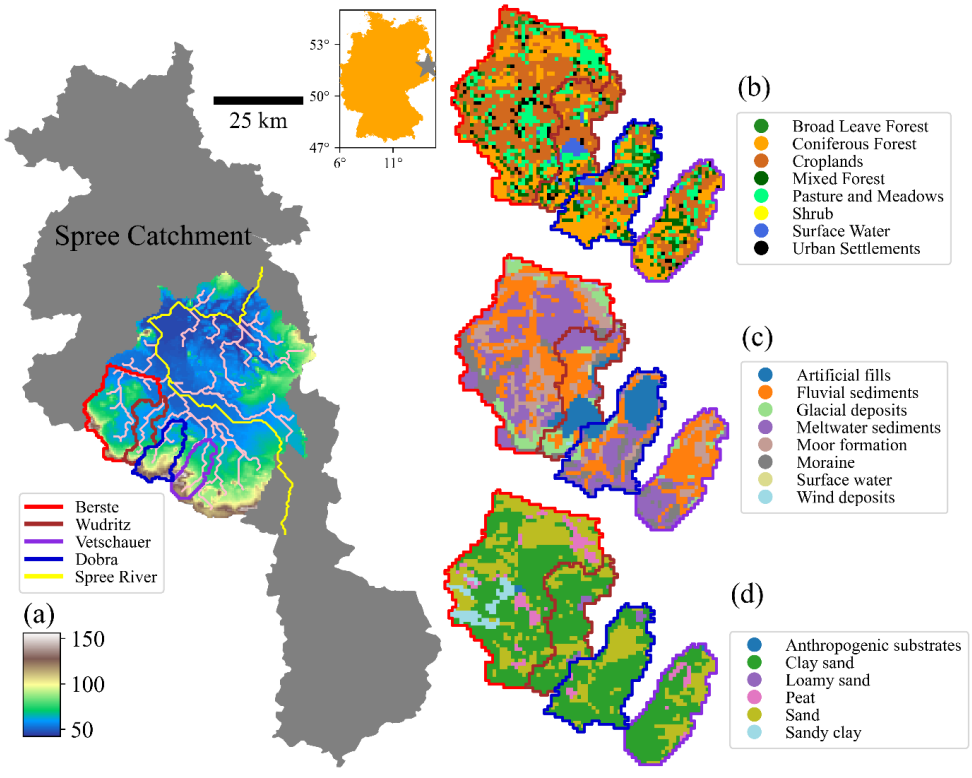

Figure 1. (a) Elevation, river network and catchment borders, (b) land use, (c) geology, and (d) soil types of the four sub-catchments in the MSC.

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Table 1. Catchment characteristics of the MSC and its sub-catchments (Berste, Wudritz, Dobra, Vetschauer)

Land use (%)	MSC	Berste	Wudritz	Dobra	Vetschauer
Urban settlements	5.5	5.2	3.5	3.0	4.2
Surface water	2.9	0.2	7.7	3.0	0.7
Pasture and meadows	19.2	17.2	12.3	13.7	13.7
Croplands	30.6	48.4	44.9	25.6	33.9
Shrub	0.8	0	0.5	0.4	0.2
Coniferous forest	29.7	20.6	18.5	36.6	30.4
Mixed forest	8.5	6.5	8.1	12.0	14.1
Broad leave forest	2.8	1.9	4.5	5.7	2.8
Geology (%)					
Artificial fills	4.7	1.0	23.7	24.1	0
Fluvial sediments	25.7	27.7	29.9	20.5	49.4
Glacial deposits	9.3	8.2	11.4	3.2	5.6
Meltwater sediments	28.0	35.0	21.0	29.8	23.7
Moor formation	17.3	18.1	5.2	5.7	12.5
Moraine	12.2	9.5	8.6	16.7	8.8
Wind deposits	2.8	0.5	0.5	0	0
Soil (%)					
Peat	8.5	7.3	0	1.5	5.1
Clay sand	29.7	51.4	70.9	71.0	66.6
Sand	58.7	34.1	24.9	26.2	27.4
Clay	0.6	0	0	0	0
Sandy clay	1.1	6.8	0	0	0
Anthropogenic substrates	1.1	0.4	0	0	0.9
Loamy sand	0.3	0	4.2	1.3	0
Area (km^2)	2806.3	316	101.3	131.8	107.8

2.2 The STARR model and adaptations to simulate low-relief and different land use

The spatially distributed tracer-aided rainfall-runoff (STARR) model (van Huijgevoort et al., 2016) integrates the general conceptual structure of the HBV-light hydrological model (Lindström et al., 1997; Seibert and Vis, 2012) in a distributed, gridded framework that enables flux tracking of water and tracers through catchments. It is operated in the PCRaster Python framework (Karssenberg et al., 2010). The STARR model includes a module for tracking of stable water isotopes and tracer mixing (van Huijgevoort et al., 2016; Ala-aho et al., 2017). As a fully distributed model, hydrological fluxes are simulated in each grid cell based on a simple reservoir structure and water balance equations (Figure S1). This has been successfully applied in TAMs across a range of catchments at multiple scales (0.2-2500 km^2) in contrasting

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environments (Ala-Aho et al., 2017; Correa et al., 2020). The basic hydrological components and a brief summary of the STARR model are given in the supplementary materials (Appendix A), while van Huijgevoort et al., (2016) and (Dehaspe et al., 2018) provide more detailed descriptions.

Some of the assumptions of the STARR model, which was originally developed for mountainous catchments subsequently adapted for tropical and cold regions, are not applicable in the lowland catchments studied here (the detailed equations used in modified STARR model are shown in Table S1). The topographical wetness index was not used to separate hillslope and lowland areas for runoff generation as in previous applications. Further, runoff routing was determined by the Manning equation (Chow, 1959), rather than assigning a pre-defined velocity.

Further, fractionation of stable water isotopes by evaporation in soil and interception storage was adapted to follow the Craig-Gordon model (Craig and Gordon, 1965), rather than being simulated by empirical representations (as in van Huijgevoort et al., 2016, Correa et al., 2020). The partitioning of evapotranspiration (ET) in the original STARR model was not applicable in the MSC as the isotopic composition of evaporation was sometimes more enriched than calculated isotopes of ambient atmospheric vapour (Chakraborty et al., 2018). Therefore, the partitioning method from HYDRUS-1D (Simůnek et al., 2013) was used here, where the transpiration originates from, and is linearly related to, soil and groundwater saturation. In order to keep parameter consistency, we adapted the interception module to the one developed in the HYDRUS-1D and the EcoPlot models (Stevenson et al., 2023), with the interception volume and the maximum capacity being controlled by LAI. Channel grid cells were distinct in representing different runoff and routing processes. Roughness (Manning coefficient) used

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in the kinematic wave equation was defined as 0.025 in the channel grid cells as recommended in Chow (1959), while other non-channel grid cells were assigned the values similar to van der Sande et al., (2003) and according to the land use (Table S2). The channel width used in the kinematic wave equation was estimated from recent Google earth maps (03.08.2024), while the width for non-channel grid cells was defined as the grid cell size (i.e., 500 m). Other parameters were the same for all grids. Explicit parameterization of anthropogenic factors (i.e., major water withdrawn in Berste, restored lakes in Wudritz and Dobra) was excluded due to insufficient data, and the influences will be evaluated.

2.3 Data Acquisition

2.3.1 Forcing Datasets

The spatial resolution of the model grid was defined at 500 m as a trade-off between adequate spatial detail and computation time (Smith et al., 2021). All datasets listed in Table 2 were downscaled or upscaled to the same resolution for consistency.

The meteorological inputs were acquired from twenty weather stations in or near the study catchments (i.e., measuring precipitation (P), temperature (T), relative humidity (RH)) and grid products of potential evapotranspiration (PET) operated by the German Weather Service (DWD) were used, and the station datasets were linearly interpolated to spatially distributed (500 m) inputs. The 8-day composite LAI dataset at 500 m resolution (MCD15A3H V6.1) was used to characterise LAI dynamics. The dataset was accessed through Google Earth Engine (GEE). The cloud masking process was based on GEE and linear resampling at daily resolution was conducted, corresponding to the other input datasets. A global product to estimate the stable water isotopic composition (Interannual Monthly Mean values) of rainfall from (Bowen

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and Revenaugh, 2003) was used and set as daily rainfall isotope input to the model constant in each month and equal to the monthly product value.

2.3.2 Datasets for model calibration and evaluation

Daily discharge from 2018 to 2023 and seasonal streamwater isotope data were collected during 2021-2023 in the four catchments at the Bruckendorf (Berste), Ragow (Wudritz), Boblitz (Dobra), and Vetschau (Vetschauer mill creek). Gauging stations (Figure 1) were used for model calibration (Table 2). Stable isotopes were sampled every season over three years (2021, 2022, 2023) at the river outlet of the four catchments (for detailed sampling procedure refer to Chen et al. (2023)). Further, MODIS ET (MOD16A2GF from GEE) and PML ET (Zhang et al., 2019) 8-day composite products were compared with simulation results to evaluate evapotranspiration simulation. Despite uncertainties, the PML product aligned better with flux tower (51.8922 N, 14.0337 E) records in the Spreewald (Table 2) indicating its usefulness as a comparator for modelling results (Figure S2).

Table 2. Overview of the datasets used in this study

Forcing datasets	Temporal resolution and period	Spatial resolution
P, T, RH	Daily; Jan 2014 - Dec 2023	20 stations
PET	Daily; Jan 2014 - Dec 2023	1 km × 1 km cells
Discharge	Daily; Jan 2014 - Dec 2023	4 stations
Rainfall isotopes	Monthly; Jan 2014 - Dec 2023	5 × 5 arc minutes
LAI	8 days; Jan 2014 - Dec 2023	500 m × 500 m cells
Calibration datasets		
Discharge	Daily; Jan 2014 - Dec 2023	4 stations
Streamwater isotopes	Seasonally; Jan 2021 - Dec 2023	4 sample locations
Evaluation datasets		
PML ET	8 days; Jan 2014 - Dec 2023	500 m × 500 m cells
MODIS ET	8 days; Jan 2014 - Dec 2023	500 m × 500 m cells
FLUXNET	Daily; Jan 2011 - Dec 2014	1 station in the Spreewald

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2.4 Model parameterisation, sensitivity analysis and calibration

2.4.1 Model parameterisation

The number of calibrated model parameters was minimised and therefore some of the parameters were assigned fixed values (Table S2). In total, 35 parameters were included for calibration and the assigned ranges for calibration were mostly adapted from previous applications of the STARR model, with some adjustments appropriate to the characteristics of the study catchments (Table S2). Parameters representing soil characteristics were distributed according to land use types (i.e., urban, water, pasture, cropland, shrub, forest) given the close correlation between land cover and soil type in the region (see (Smith et al., 2021)). The flux processes from interception to soil storage (throughfall and stemflow) are different in forest and non-forest land use, as contrasting canopy characteristics affect the rainfall partitioning (Guevara-Escobar et al., 2007), and the corresponding parameters were determined separately.

2.4.2 Sensitivity analysis (SA)

We employed the Morris Method (Morris, 1991) to identify the sensitive parameters. The calculation used the SAFE tool (Sensitivity Analysis for Everybody, Pianosi et al., 2015). The elementary effects (reflecting the sensitivity of each parameter) were calculated through perturbing the starting parameter by a certain variation based on a radial one-at-a-time strategy. Nash Sutcliffe Efficiency (NSE) (Hodson, 2022) of simulated streamflow or streamwater isotopes, corresponding to calibration scheme, was used as the objective function in calculating the elementary effects (Table 3). The Latin-Hypercube sampling method (Pianosi et al., 2015) was selected to determine the starting parameter and following perturbation. The mean elementary effect of each parameter was used to indicate the sensitivity of the corresponding parameters. Parameters related to pastures, croplands, and forests were more sensitive than

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others, as they cover majority of the catchment area (Table 4), and the estimated ecohydrological fluxes are mainly shown for these three land uses.

2.4.3 Model calibration

The modified STARR model was run at daily time steps for the period from 2014 to 2023. A 4-year spin-up period (2014-2017) was applied, and the remaining six years were used for calibration. The multi-objective non-dominated sorting genetic optimization algorithm II (NSGA-II) (Blank and Deb, 2020; Deb et al., 2002) was applied to derive the Pareto-optimal solutions. Five distinct calibration schemes were conducted based on measurements (i.e., streamflow and/or stream isotopes) at the outlet of the four catchments and are detailed in Table 3. The first scheme (discharge-only based calibration) was calibrated only on the streamflow of all four catchments (multi-gauged streamflow calibration) using the NSE values of simulated streamflow as the objective function. Considering the potential for heterogeneity in the hydrological functioning of each catchment and to assess the additional information content of the isotope data in the modelling, calibrations (the other four schemes as in Table 3) were also carried out in each catchment independently and based on NSE values of simulated streamflow and isotope (isotope-aided calibrations) (Table 3). Simulations based on NSGA-II were conducted with 40 generations and 200 individuals in the population per generation, and the first pareto front in the 40^{th} generation were employed as the solution. No validation period was employed, as the present study attempted to better constrain ecohydrological processes in the MSC, rather than for forecasting applications. Further, calibrating to the full available data and skipping model validation has been found more robust than the traditional split-sample approach in hydrological modelling (Shen et al., 2022).

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Table 3. Five calibration schemes based on measured streamflow and isotope at the outlet of the four catchments. Sensitivity analysis was conducted separately on isotope and discharge measures in schemes 2-5.

Calibration scheme	Streamflow	Isotope	Objective function in SA
Scheme 1	Berste Wudritz Vetschauer Dobra		$\sum_i NSE_i$, i includes streamflow in all sub-catchments used in the scheme
Scheme 2	Berste	Berste	$NSE_{streamflow}$ or $NSE_{isotope}$
Scheme 3	Wudritz	Wudritz	$NSE_{streamflow}$ or $NSE_{isotope}$
Scheme 4	Vetschauer	Vetschauer	$NSE_{streamflow}$ or $NSE_{isotope}$
Scheme 5	Dobra	Dobra	$NSE_{streamflow}$ or $NSE_{isotope}$

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3 Results

3.1 Model performance

3.1.1 Discharge simulations

Table 4. The 6 most sensitive parameters in each calibration scheme. Subscript p, c, f represent pasture, croplands, forest, respectively. kS, kG LP, INT_α, K control processes of runoff from soil, runoff from groundwater, Actual ET, interception and ET partitioning, respectively; and FC is the soil water storage capacity.

Scheme1	**Scheme2**		**Scheme3**		**Scheme4**		**Scheme5**	
Discharge	isotope	discharge	isotope	discharge	isotope	discharge	isotope	discharge
kS_f	kS_c	kS_c	kS_c	kS_c	kS_f	kS_f	kS_f	kS_f
kS_c	K	kS_f	kS_f	kS_f	K	kS_c	kS_c	kS_c
kS_p	LP_c	kS_p	LP_c	kS_p	kS_c	kS_p	kS_p	kS_p
LP_f	FC_c	LP_c	FC_c	LP_c	INT_α	LP_f	LP_f	LP_f
LP_c	kS_f	FC_c	k	FC_c	kG	FC_f	K	FC_f
FC_c	k_G	INT_α	kS_p	INT_α	kS_p	INT_α	FC_f	INT_α

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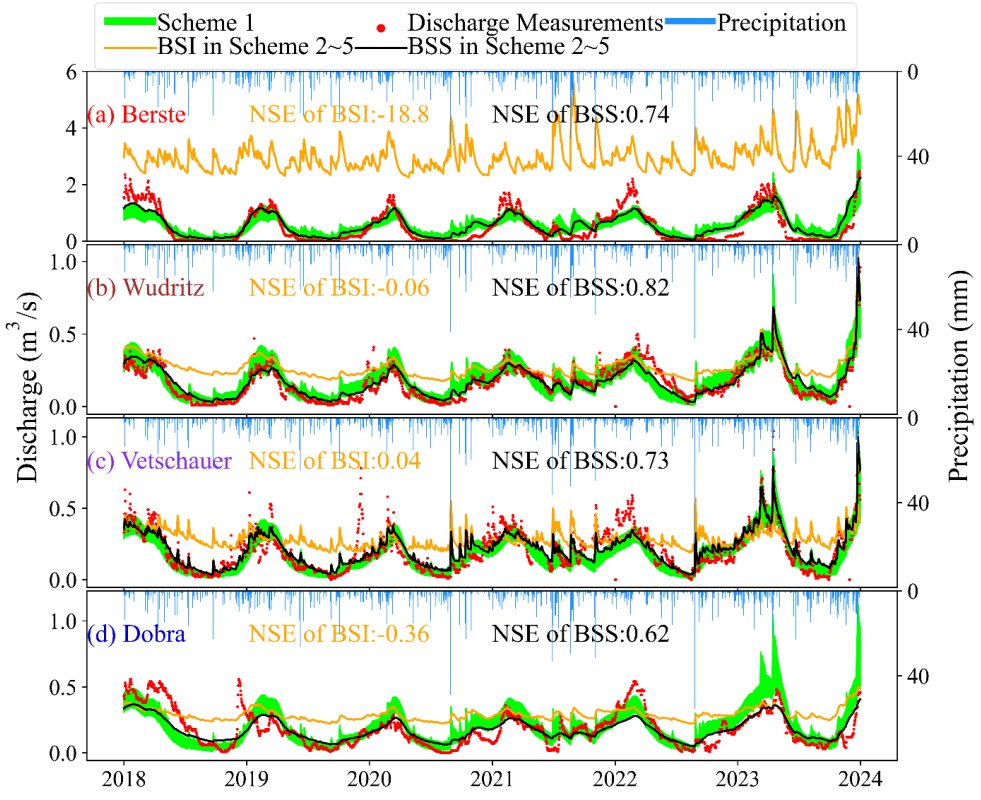

Figure 2. Discharge simulations at the outlet of each catchment based on each calibration scheme. (a) Berste; (b) Wudritz; (c) Vetschauer; (d) Dobra. "BSI" and "BSS" are abbreviations for the simulation with Best Simulated Isotope and Best Simulated Streamflow, respectively.

Discharge-only based calibrations (scheme 1) and parameter sets with the best simulated streamflow (BSS) in isotope-aided calibrations (scheme 2-5) successfully captured discharge dynamics in each catchment with average NSE (Figure 2) mostly >0.6 (Table 5). The uncertainty bands in scheme 1 were relatively large, but bracketed the measurements for most of the time at most sites (Figure 2). The averaged NSE were slightly lower than BSS in schemes 2-5, suggesting the trade-offs in balancing performance across the four individual catchments. However, variations in scheme 1 and BSS (schemes 2-5) generally underestimated peak flows

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and overestimated base flows. Parameter sets with the best simulated isotopes (BSI) in schemes 2-5 gave large biases in modelled streamflow compared to measurements, showing much higher base flow, lower variations, and higher frequency of high flows, particularly in Berste and Vetschauer where pronounced overland flow contributions were simulated (see section 3.2.2).

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349 3.1.2 Isotope dynamics

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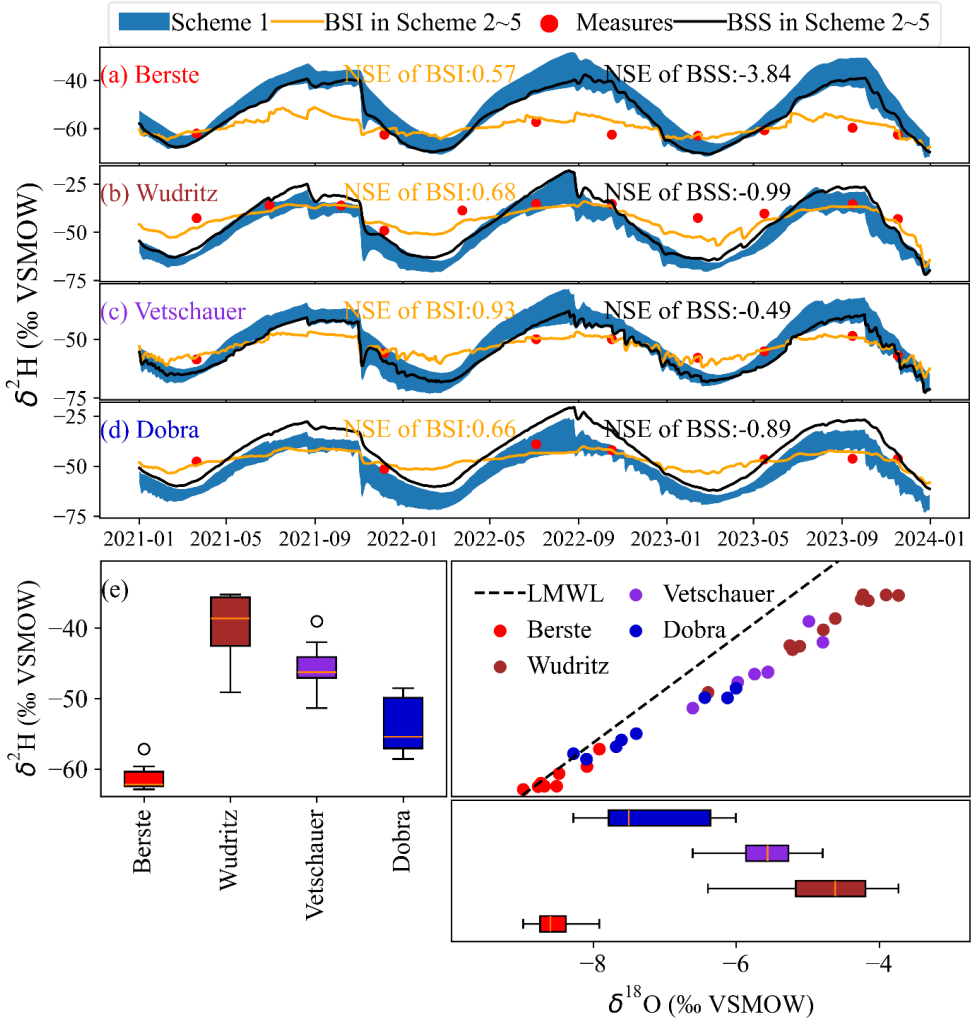

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352 *Figure 3. Isotope simulations at the outlet of each catchment based on each calibration scheme.*

353 *(a) Berste; (b) Wudritz; (c) Vetschauer; (d) Dobra; and (e) Dual isotope plots for streamwater*

354 *isotopes from Jan 2021 to Dec 2023 in each catchment.*

355

356 The stream isotope signatures in the four catchments showed contrasting characteristics.

357 Overall, apart from the Berste, streamwater isotopes in each catchment plotted below the local

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meteoric water line (LMWL), reflecting fractionation processes. The similar alignment of isotopes along a shared local evaporation line indicates comparable atmospheric moisture demand among the catchments (Figure 3). The Berste exhibited the most depleted isotopic signature (δ^2H: ~ -62‰), while Wudritz was the most enriched catchment (δ^2H: ~ -38‰), and their enrichments positively correlated with the extent of surface water area, although all catchments have low surface water coverage (< 8%) (Figure 3). Simulations in scheme 1 and BSS in schemes 2-5 reproduced the seasonal isotope dynamics, with summer enrichment and winter depletion (Figure 3). However, the variability of isotopes was overestimated, although mean simulations and measurements were comparable. This showed that different flow paths, mixing processes and fractionation effects in the catchments were problematic in the discharge-only based calibrations (scheme 1) or BSS in isotope-aided calibrations (schemes 2-5). BSI in schemes 2-5 yielded much more consistent simulations of the isotope dynamics, although this came at the cost of much poorer discharge performance (Figure 3). The low NSE values between simulations and measures are because of the coarse temporal scale of samples and deviations in single sample point could result in large degradation in NSE values (Table 5).

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Table 5. NSE and KGE values for discharge and isotopes at different locations based on the different schemes. Values at multiple locations were only calculated in calibration scheme 1, while the metrics of the other four schemes ("schemes 2-5") were given at corresponded calibrating outlets (i.e., values in Berste, Wudritz, Dobra and Vetschauer are from Shemes 2-5, respectively). The slash "/" separates results in the two ends of the pareto front, namely "BSS/ BSI".

Locations	**Scheme 1**				**Schemes 2-5**			
	Discharge		Isotope		Discharge		Isotope	
	NSE	KGE	NSE	KGE	NSE	KGE	NSE	KGE
Catchments								
Berste	0.69	0.57	-55.9	-3.93	0.74/-18.8	0.66/-4.03	-42.0/-1.05	-3.84/0.57
Wudritz	0.77	0.83	-7.85	-0.76	0.82/-0.06	0.85/0.24	-5.18/-0.02	-0.99/0.68
Vetschauer	0.63	0.66	-2.48	-0.77	0.73/0.04	0.75/0.17	-1.44/0.96	-0.49/0.93
Dobra	0.46	0.69	-4.30	-0.56	0.62/-0.36	0.56/0.02	-5.95/0.51	-0.89/0.66

3.2 Trade-offs between streamflow and isotope-based calibrations

3.2.1 Pareto front of simulations

The Pareto front of simulations from schemes 2-5 show the range of potential solutions of streamflow and isotopes. Points in the middle of the Pareto front represent the compromised "trade-off" solutions based on both streamflow and isotopes (Figure 4). Berste resulted in lower NSE or KGE of both isotopes and streamflow than the other three catchments, while the compromised trade-off solutions in Vetschauer were most satisfying, and its Pareto front was the narrowest (Figure 4). The unsatisfactory solutions for Berste reflected the conflicting information provided by isotope and streamflow data under the existing model structure and potentially reflected unknown processes resulting from the intense management.

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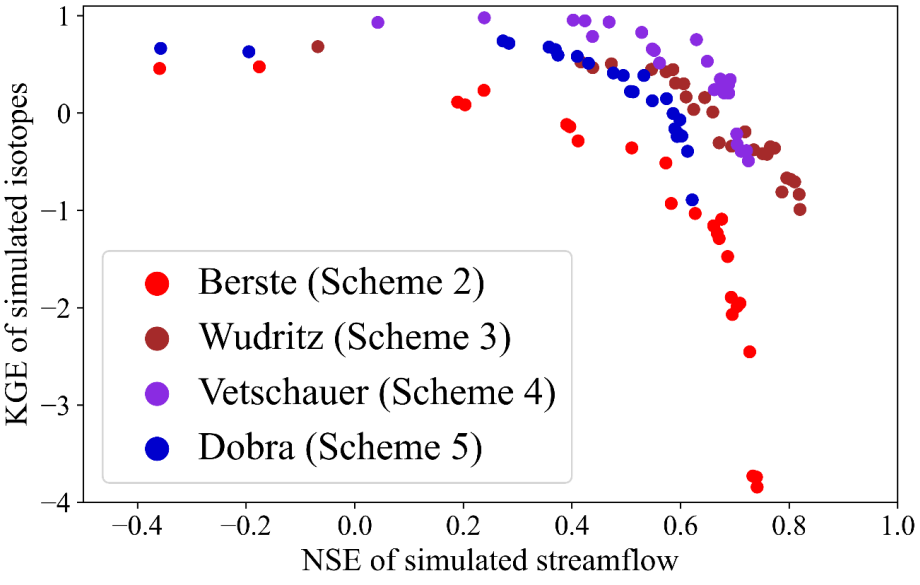

Figure 4. Pareto front of simulations in schemes 2-5. Simulations on two ends of the front were excluded in this plot. KGE of the compromised solutions in Berste, Wudritz, Vetschauer and Dobra can reach 0.14/0.23, 0.54/0.45, 0.62/0.75 and 0.43/0.40 in streamflow/isotope.

3.2.2 Impact of calibration on contributing runoff generation processes

Runoff generation from soil storage was the most sensitive hydrological processes in the simulations in all calibration schemes (no matter whether isotope measures were considered), while groundwater contributions were highlighted by isotopes in Berste and Vetschauer (Table 4). According to the solutions on the Pareto front, runoff was mostly generated from the soil and groundwater storages, while overland flow was limited in the pasture in the winter or spring of the wet year of 2023 in two of the catchments (Figure 5). For the parameter sets that produced the best streamflow simulations, runoff was mainly sourced from the shallower soil stores in all three major land uses, while this contribution gradually decreased in simulations for the opposite end of the Pareto front with groundwater sources being more important for simulations with better isotope performance (Figure 5).

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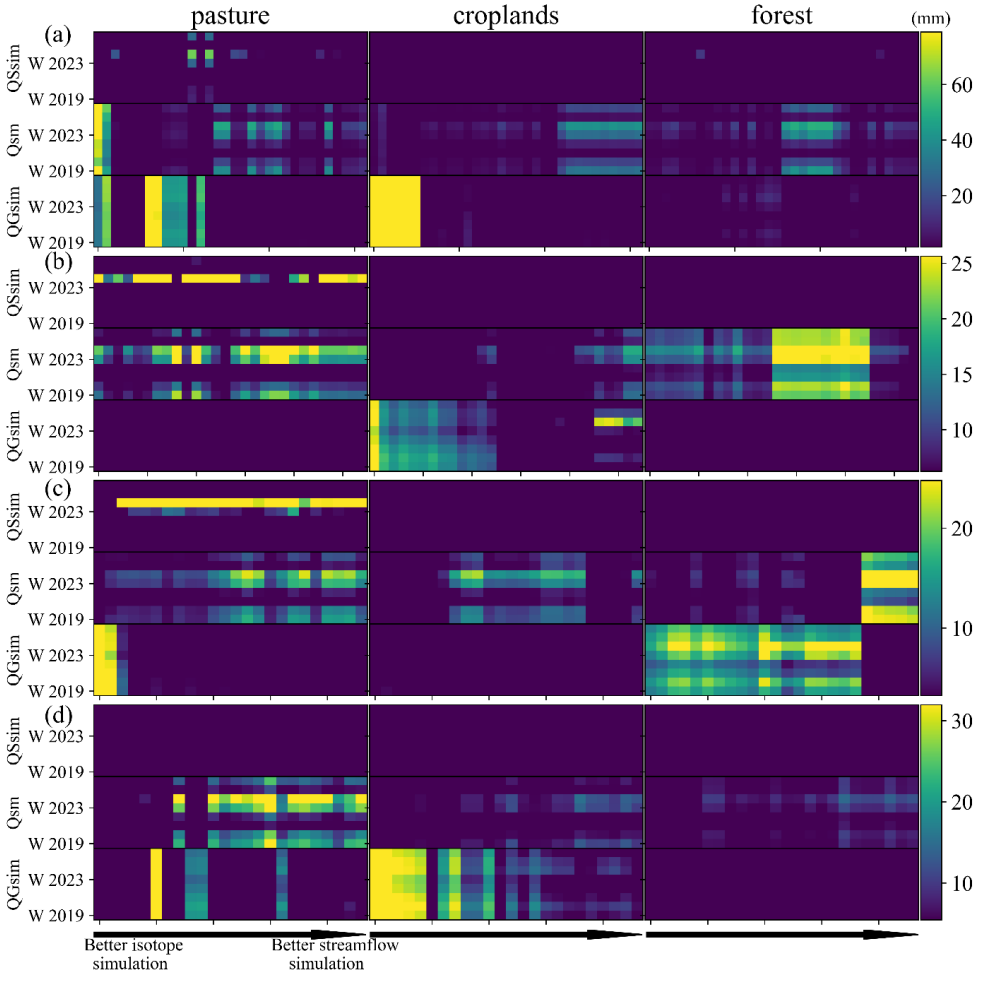

Figure 5. Total seasonal runoff from contrasting sources for three land uses for each catchment during 2019 and 2023 (winter, spring, summer, fall of 2019 and 2023 along Y-axis from bottom up, and "W" in the Y-label means winter) in the first Pareto front of (a) Berste (scheme 2); (b) Wudritz (scheme 3); (c) Vetschauer (scheme 4); (d) Dobra (scheme 5). "QGsim" and "Qsm" represent runoff from groundwater and soil water, respectively, while "QSsim" is instantaneous overland flow. Each pixel in the plot is the total seasonal amount of runoff. The X axis from left to right represents results from BSI to BSS.

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Runoff generation from soil and groundwater storages showed seasonality with higher streamflow in winter. This pattern was further intensified during the wet year of 2023 (Figure 5). Runoff from soil in parameter sets with better simulated streamflow presented lower influence in croplands of all four catchments. Runoff from groundwater in simulations with better isotope performance was more evident in croplands than the other two land uses, except for the Vetschauer catchment (Figure 5). Subsurface water flowing through capillary flux (from groundwater storage to soil) and soil seepage (soil to groundwater) was consistent along the Pareto front of Wudritz and Dobra, with high contribution of both fluxes in croplands (Figure S3). The stronger influence of subsurface processes in Berste and Vetschauer was only re-produced in simulations with better isotope performance (Figure S3).

3.2.3 Impact of calibration on ET estimates and ET partitioning

The sensitivity of parameters controlling the movement of water to the atmosphere (ET) was important, although they had contrasting order in each calibration scheme. Except for the underestimated ET in parameter sets with better simulated isotopes in Berste, parameter sets along the Pareto front had consistent annual ET volume in each catchment (from 400 to 500 mm/year in dry to wet years), and mostly aligned with both satellite estimates. ET showed strong seasonality with peaks in spring and summer in model simulations (Figure 6; Figure S4). This aligned with the satellite ET observations. Simulations at both ends of the Pareto front showed higher springtime ET yet lower modelled ET in summer across all catchments compared to the remote sensed products, except for BSI in Berste. These differences decreased during wet summers (e.g., 2021 and 2023) (Figure 6; Figure S4). BSI (except for Berste) in schemes 2-5 had lower spring ET and higher summer ET compared to BSS. This seasonal shift in BSI aligned better with temporal patterns of remote sensed ET (Figure 6).

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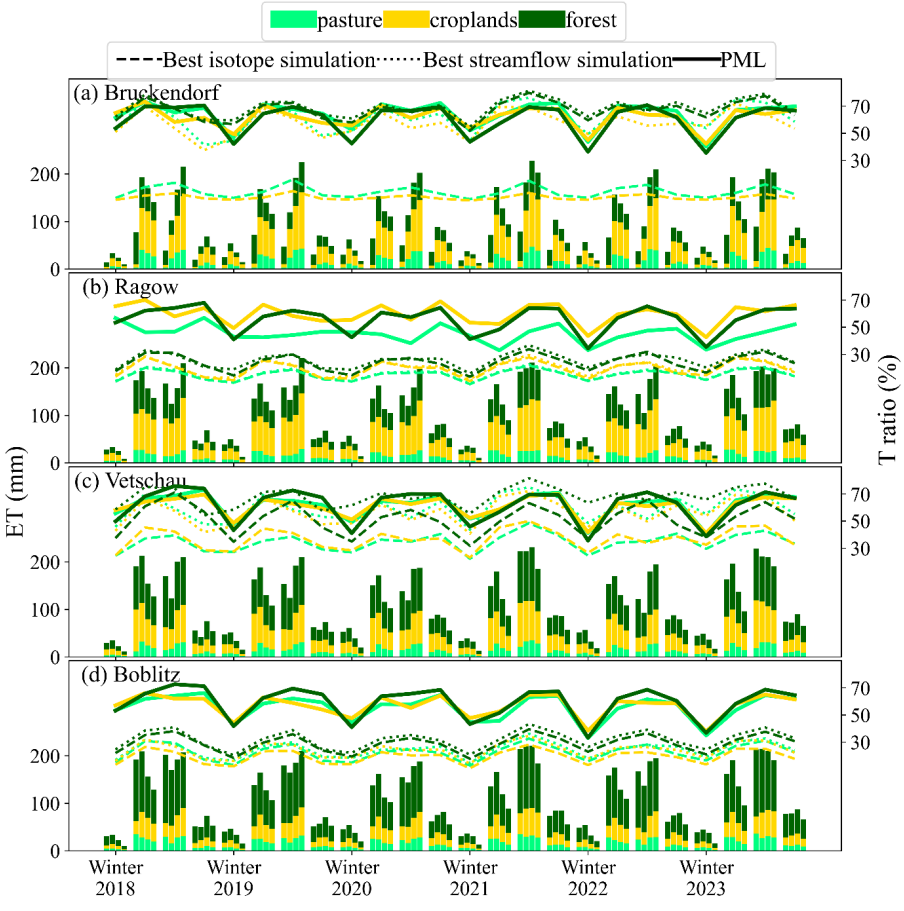

Figure 6. Seasonal total ET and transpiration ratio (T/ET) from simulations (a) Berste in scheme 2; (b) Wudritz in scheme 3; (c) Vetschauer in scheme 4; (d) Dobra in scheme 5, and RS products. Bars and lines indicate ET and T ratios, respectively. Each season contains four bars, ordered from left to right as follows: simulation with best simulated isotope and best streamflow, MODIS and PML ET products. ET values from each land use were scaled according to their area proportion, and the stacked bar value approximately represents the total seasonal ET of the sub-catchment.

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Simulations in scheme 1 and BSS (schemes 2-5) exhibited higher consistency with spatial patterns of MODIS ET compared to BSI (schemes 2-5). Additionally, elevated ET was consistently captured along the channel reach in Berste, the upper catchment in Wudritz, and across the whole catchment of Vetschauer and Dobra (Figure 7), although the simulated spatial variability in ET remained less pronounced than the MODIS estimates. However, high ET in the PML product was more consistent with croplands distribution, which indicated the potential irrigation in croplands that has not been conceptualized in the current model structure (Figure 7).

In terms of ET partitioning (into E and T), soil water storage capacity became more sensitive for simulations constrained by isotopes as the corresponding parameters ranked higher compared to discharge-only based simulations. This is consistent with the importance of fractionation in the variation of isotopes (Table 4). In all catchments, the transpiration ratio from each land use had similar temporal dynamics (summer peaks and winter troughs), and was higher in forest than in the other two land uses (Figure 6; Figure S4). In Vetschauer, most simulations of transpiration ratios in the Pareto front in all three land uses aligned with the PML estimates, with 50-70% and 30-40% (dependent on land use; with forest being higher) in summer and winter shown in compromised solutions, respectively, although with slightly lower values in BSI. The consistent and high transpiration along the Pareto front was shown in Berste, and only some of the better simulated isotope simulations in the Pareto front highly underestimated transpiration (Figure 6, Figure S4). In contrast, simulations (schemes 2 and 5) in Wudritz and Dobra showed notably lower transpiration ratios, and only a small part of simulations in the Pareto front reached RS levels (Figure S4).

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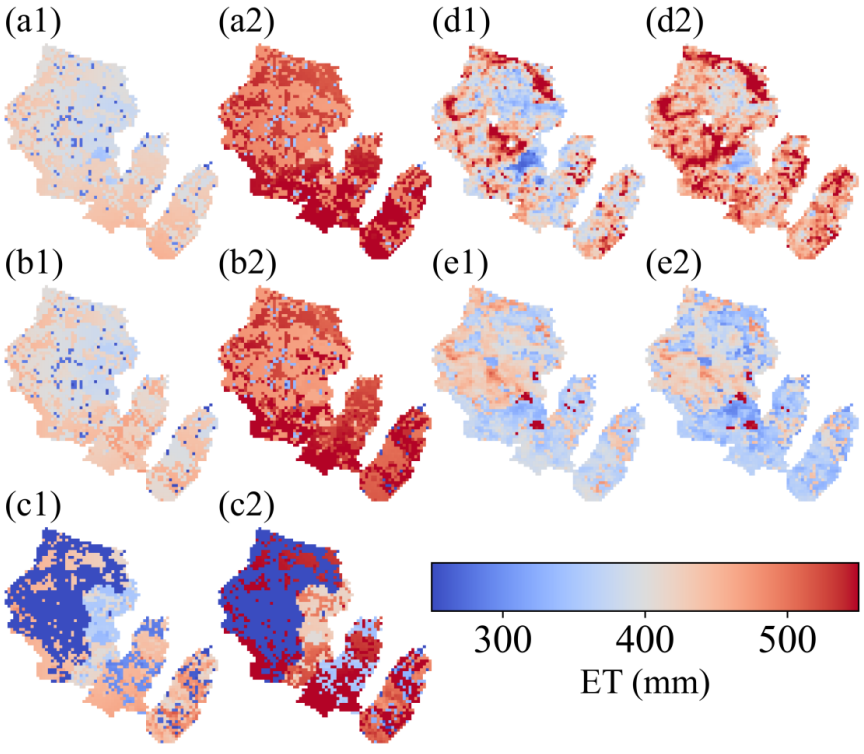

Figure 7. Spatial distribution of ET in the four catchments. (a) Scheme 1; (b) BSS in schemes 2-5; (c) BSI in schemes 2-5; (d) MODIS ET; (e) PML ET. Suffix "1" and "2" means dry year of 2019 and wet year of 2023, respectively.

3.3 Quantification of the water balance components

The partitioning into different water balance components was relatively consistent across all catchments, irrespective of the calibration schemes (Figure 8). ET was the dominant output flux, especially during the spring and summer period (> 90%). Simulations showed that soil storage played the major role in supplying water for ET in spring and early summer and was subsequently replenished during autumn and winter. Discharge accounted for a minor proportion of the water balance (~5%). Variations of groundwater storage in each season were small (<1% of the total water balance) in simulations calibrated on discharge alone, while it

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increased to ~5 - 30% (catchment dependent) when isotopes were included in calibrations (Figure 8). With isotopes in calibrations, simulated groundwater storage declined during spring and summer and was replenished in winter and fall, with the variation being the most substantial in Vetschauer.

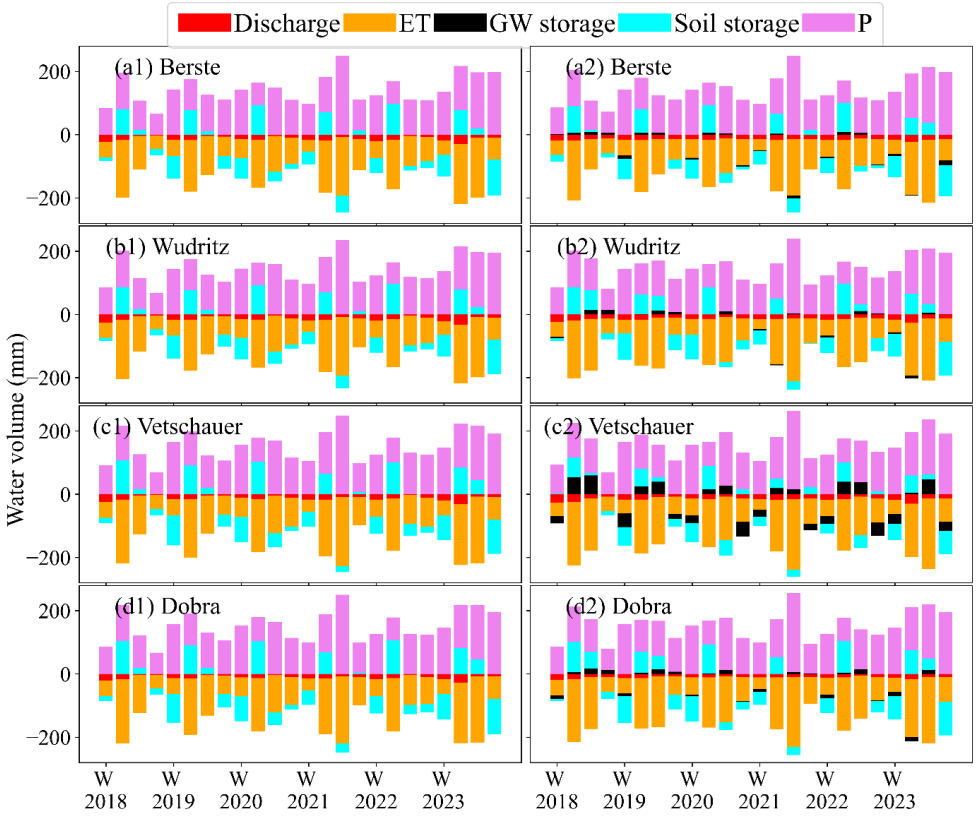

Figure 8. Seasonal water balances in the four catchments. (a) Berste; (b) Wudritz; (c) Vetschauer; (d) Dobra. Suffix "1" and "2" means averaged values of all simulations in the Pareto front of scheme 1 and a compromised solution in schemes 2-5, respectively. Positive bars represent water sources, while negative bars are water losses. "Channel storage" and "Interception storage" were too small compared to other components to show in the figure.

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4 Discussion

4.1 Model success for streamflow and isotope dynamics

Streamflow usually serves as a key indicator of water resource availability and is widely used in hydrological model calibration due to its broad accessibility. Previous work using isotopes and other tracers has shown that calibration on streamflow alone can lead to misleading conceptualization of hydrological processes (Ala-Aho et al., 2017; van Huijgevoort et al., 2016; McDonnell and Beven 2014). However, similar to most studies based in environments where blue water fluxes (i.e. streamflow and groundwater recharge) are greater than green water fluxes (i.e. ET fluxes that sustain vegetation growth), here, streamflow dynamics and overall runoff volumes were also effectively captured by discharge-only based calibrations in an ET-dominated region. However, slight overestimations occurred during winter peaks and underestimations during summer low-flow periods. In addition, modelled annual ET estimates aligned closely with RS ET products (e.g., MODIS or PML), with ET amounts ~400 - 500 mm/year from dry (e.g., 2018) to wet (e.g., 2023) years and deviation of around ± 50 mm/year. Although groundwater recharge was sometimes underestimated (especially in Berste), rough partitioning of precipitation into green and blue water fluxes was accurately constrained by streamflow in the calibrations. Similarly, in other literatures, multi-criteria calibrations incorporating both streamflow and RS ET demonstrated marginal improvements in annual ET or streamflow estimates, compared to discharge-only based calibrations, albeit with reduced parameter equifinality (Oliveira et al., 2021; Shah et al., 2021).

However, discharge-only based calibrations normally exhibit significant uncertainty in representing internal hydrological processes, owing to high degrees of model freedom and non-identifiable parameters (Herrera et al., 2022). This was evidenced by the large uncertainty bands in the simulated variables (for both streamflow and isotopes) under scheme 1. Moreover,

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catchment discharge, as an output integrating upstream hydrological processes, provides only limited insight into spatially distributed partitioning of water volumes and flow paths (Fatichi et al., 2016). This limitation becomes more pronounced as models incorporate more complex spatial disaggregation and physics-based process representations (Sun et al., 2017). A multi-gauge regional streamflow calibration normally improves the spatial representativeness of simulations and provides a greater constraint on relationships between catchment characteristics and streamflow dynamics (Liu et al., 2020). However, internal mixing and runoff generation processes (evidenced by isotope dynamics) under scheme 1 (which was a multi-gauge streamflow calibration) did not show much difference to the single-gauge calibrations (i.e., parameter set with best simulated streamflow in schemes 2-5). Improvements on simulations of subsurface processes were also not clear in other literature (Wanders et al., 2014). Furthermore, sensitivity analysis revealed that discharge was more sensitive to soil drainage process in all three major land uses (i.e., forest, croplands, pasture) of the four studied catchments, and parameters controlling other hydrological processes were less identifiable.

Incorporating stable water isotopes into modelling improves our understanding of ecohydrological processes and storage dynamics. Multi-criteria calibration using both streamflow and isotope enables exploration of a broader parameter space to satisfy multiple calibration objectives (Holmes et al., 2020). Subsurface processes in the deeper layer (e.g., seepage and capillary flux in the present model) are inherently challenging to constrain in modelling through only near-surface observations (e.g., ET, soil moisture), and these processes are usually poorly understood (Beven, 2006). Stable water isotopes are powerful in this regard as they integrate the cumulative effects of water flow paths and mixing across all hydrological storages (Godsey et al. 2010). Our TAM revealed that discharge-only based calibration or parameter sets with better simulated streamflow in isotope-aided calibrations does not

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accurately capture such mixing processes, as their simulated isotopes are different from observations. Model simulations that reconciled simulated and observed isotopes represented better mixing between soil water and groundwater storage. Increased runoff from groundwater, characterized by depleted isotopes, modulated modelled outflow signatures, flattening the seasonal isotopic variability, and thus, increasing process representation. This aligns with previous findings where dominant subsurface flows produce subtle isotopic variations (Iorgulescu et al., 2007; Oerter and Bowen, 2019) and where contrasting isotope signatures across water stores are key to disentangling water mixing processes (Kirchner, 2003).

The fractionation of stable water isotopes is governed by evaporation, and measured isotopes at the catchment outlet reflected the aggregated evaporation rates across the whole catchment. Parameters controlling ET processes (e.g., FC and LP) exhibited greater sensitivity when using isotopes as a calibration target, supporting its value as a constraint on ET dynamics in simulations. Despite this, total (bulk) seasonal ET volumes across the catchments showed minimal variations along the Pareto front, implying that streamflow and isotopes similarly constrain bulk ET estimates. The use of temporally quite coarse isotopic datasets – necessary at such large spatial scale – and inter-annually averaged rainfall isotope inputs in this study likely introduced uncertainty in ET process constraints, and higher-resolution data can better capture temporal variability in fractionation intensity (Sprenger et al., 2017). This is consistent with broader findings: while isotopic tracers are widely recognized for improving estimates of E/T partitioning (Gibson and Edwards, 2002), their utility in refining total ET quantification remains less clearly demonstrated, particularly at larger spatial scales.

4.2 Water flux partitioning and influences of management measures

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Compared to simulations in the Berste, the ecohydrological partitioning was more reliably represented in the Wudritz, Vetschauer and Dobra, as NSE or KGE of both streamflow and isotopes reached > 0.4 in the compromised solutions (middle part of Pareto-optimal solutions). In these catchments, runoff was predominantly generated from groundwater and soil storage, reflecting a subsurface-process dominated flow regime. This pattern aligns with observations across much of the Spree catchment, where subsurface-driven runoff mechanisms are widespread (Chen et al., 2023). Runoff in the upper Spree catchment is predominantly groundwater-driven (Kröcher et al., 2025), a pattern consistent with the Vetschauer catchment, and likely shared by the Berste, as evidenced by depleted isotopic signatures. In contrast, the Wudritz and Dobra catchments showed rather lower proportions of groundwater contributions. This aligns with historically depressed groundwater levels caused by pumping during regional de-watering from mining activities (Arndt and Heiland 2024). In addition, the influence of groundwater in the studied four catchments may potentially increase, as the opencast mines have been closed for 30 years and it is unclear to whether groundwater levels have fully stabilized (Kröcher et al., 2025). The increased temperature and shift of precipitation from summer to winter due to climate change also possibly leads to increased ET during winter and spring reducing discharge and groundwater recharge accordingly. This could result in contrasting water distributions in each season, and intensifying negative climatic water balance in the local environment (Pohle et al., 2012).

In Wudritz and Dobra, isotope simulations optimized for streamflow accuracy produced more isotopically depleted signatures compared to the measured values. To reconcile this discrepancy, an assumption of lower proportions of transpiration in evapotranspiration (ET) was needed. The mismatch in transpiration ratios between simulations and the PML product may partially stem from unaccounted surface water evaporation. While evaporation from small

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open water bodies (e.g., ponds, channels) has negligible impacts on overall the catchment water balance, it likely plays a critical role in isotopic enrichment (Birkel et al., 2011). For instance: in the Dobra (3.0% surface water area) and Wudritz (7.7% surface water area), isotopic concentrations were likely underestimated due to unmodeled surface water evaporation. The non-linear relationship between evaporation rate and isotopic enrichment, as described by the Craig-Gordon model (Craig and Gordon, 1965), explains this dynamic: early-stage evaporation induces stronger isotopic enrichment, approaching a threshold under constant environmental conditions (e.g., humidity, temperature). Thus, even relatively minor surface water evaporation can bias isotopic signatures which then impacts ET partitioning simulations.

In contrast, at Vetschauer (0.7% surface water area), the unaccounted surface water evaporation had minor effects on the modelling due to the minimal surface water area with simulations being more comparable to the PML estimates. The ability of stable water isotopes in constraining ET partitioning was also shown in the consistency between simulations and the PML estimates, which is similar to other applications (Birkel and Soulsby, 2015). Further, the small weight of isotopes in a scalar function combining multiple objectives meant that it was possible to disentangle ET processes (Wu et al., 2023). This was also illustrated by the minor adaptations in the Pareto front from better streamflow simulations to better isotope simulations. The transpiration ratios in the simulations along the Pareto front with better simulated isotopes at Vetschauer also aligned with the other sub-catchments of the Middle Spree (Landgraf et al., 2023). The normally contrasting transpiration ratios among different land uses (Schlesinger and Jasechko, 2014) were consistent with our simulations, and contrasting LAI in each land use explains these differences (Cao et al., 2022), although the PML estimation presented similar transpiration ratios among each land use. However, the transpiration ratios could be overestimated due to unparameterized irrigation effects (Paul-Limoges et al., 2022), and the

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local water use efficiency should be further evaluated. The strong conflicts between using streamflow or isotopes as calibration constraints resulted in incorrect representation of transpiration ratios in Berste (0.3% surface water) along the Pareto front near the BSI. However, simulations near the BSS still indicated a first approximation of transpiration, considering the effectiveness of isotopes in differentiating ET partitioning.

Despite uncertainties introduced by multiple anthropogenic factors and influences, isotopes were still valuable in ET partitioning in such heavily managed catchment. Since the Middle Spree is an ET-dominated region and experiencing water scarcity due to replenishment of historical groundwater withdrawn, evaluation of local water use efficiency in the croplands is of great value for future water management. The preliminary assessment of ET partitioning through isotope-aided modelling provides strong evidence in this aspect, although its trade-offs with streamflow occasionally occurred due to unaccounted human impacts.

4.3 Reasons for trade-offs between ecohydrological fluxes and future research directions

Trade-offs in the calibrations between streamflow and isotopes are a common feature of TAM (Holmes et al., 2020), though their severity varies across applications. The extent of these compromises depends on the model's structural flexibility to assimilate additional constraints (Holmes et al., 2020). Whilst some applications based on spatially-distributed models presented slight conflicts in the information content of different calibration targets (Kuppel et al., 2018), significant degradations in streamflow is found in a lumped model after incorporating isotopes in calibration (Fenicia et al., 2008). In our study, the lack of explicit information on anthropogenic drivers (e.g., water withdrawals, irrigations etc.) emerged as a key contributor to trade-offs. Without parameterizing these factors, the model compensated by adjusting flow velocities, which failed to replicate observed streamflow celerity during rainfall

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events. The systematic biases were evidenced: parameter sets with better simulated streamflow in isotope-aided calibrations produced a soil water-driven runoff regime and underestimated baseflow, which were exacerbated by spring or summer water withdrawals altering natural flow regimes. Measured isotopic damping (flattened variations) implied slower flow velocities and greater groundwater contributions, yet the model was unable to capture these processes from streamflow dynamics alone. The strongest trade-offs occurred in the Berste catchment, where extensive croplands and likely high irrigation withdrawals amplified mismatches between simulated and observed hydrological behavior.

These trade-offs could be partially mitigated by integrating more process-based conceptualizations, though this often requires more complex parameterizations. While such enhancements improve a model's ability to simultaneously adapt flow velocity and celerity, they also introduce greater simulation uncertainty (Herrera et al., 2022). Simple explicit modeling of water extraction for irrigation (e.g., channel-to-cropland transfers) could alleviate trade-offs observed in this study. However, sparse records of withdrawal volumes and irrigation patterns, as well as political sensitivities in data sharing may limit practical modelling. The STARR model's simplified routing structure, where runoff from contrasting sources follows identical pathways to the outlet, diverges from more physics-based frameworks that better spatially differentiate the timing of contributions of overland flow, unsaturated zone flow, and groundwater flow. While this conceptual routing captured flow celerity by adjusting discharge coefficients (i.e., kS, kG), it systematically overestimated flow velocity, creating conflicts in multi-criteria calibrations (McDonnell and Beven 2014).

Conventional calibration metrics like NSE or KGE could hamper the exploration of accurate catchment processes, as single statistical performance measures are unable to capture all

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features of observed variables (Gupta et al., 1998). Seasonal isotope observations increased bias sensitivity and skewed performance assessments under the present metrics. Metrics underscoring seasonal variability could be more indicative on runoff generation processes. In order to capture observations at different temporal scales, wavelet-based objectives could be alternative in this context (Manikanta and Vema, 2022). In addition, anthropogenic activities (e.g., water withdrawn mainly occurred during spring and summer) were intensively implemented in specific seasons and not in others. Using metrics which weaken the influences of these epistemic errors in the observed streamflow could be a potential way to derive more correct parameter sets. In this regard, the limits-of-acceptability method, defining lower and upper boundaries as the tolerance of simulations deviations, is potentially useful in such heavily managed catchments (Beven, 2006), although setting the limits is still challenging due to the lack of specific information of many management interventions (Wu et al., 2025).

Despite having limited streamwater isotope samples due to the large scale of the sampled area, they were sufficient and actually very valuable to reveal some significant difference between catchments. This helped to better understand ecohydrological processes and to identify processes that were not adequately captured, such as some of the anthropogenic impacts discussed above. Isotope data at finer temporal resolution could help to better constrain ET partitioning processes in heavily modified catchments, as they certainly do in more natural environments (Soulsby et al., 2015). In addition, precipitation isotopes were from a global data product (Bowen and Revenaugh, 2003). The use of interannually averaged monthly values likely failed to capture short-term climate variability or anthropogenic influences (e.g., fossil fuel-derived vapor), introducing errors in water source apportionment (e.g., hydrograph separation) (Xia et al., 2024; Yang and Yoshimura, 2024). Again, high resolution local data would be advantageous for such investigations.

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5 Conclusions

Stable water isotopes are valuable tracers in tracking hydrological flow paths and identifying water sources, offering the potential to constrain equifinality in ecohydrological models. While model calibration in natural catchments typically exhibits slight trade-offs between isotopic signatures and conventional hydrological variables (e.g., discharge), this study advances a novel perspective on the benefits and challenges of integrating isotopes in heavily human-impacted catchments. Using the conceptual-based, fully-distributed TAM STARR, we calibrated both isotopes and streamflow without explicitly parameterizing anthropogenic disturbances to investigate three critical issues: (1) the influence of human interventions on model performance, (2) the potential of using discharge alone in calibration to mislead process interrelations from simulations under anthropogenic stress, and (3) the adaptability and value of isotopes in such contexts. We studied four sub-catchments of the Middle Spree (Berste, Wudritz, Vetschauer, and Dobra), subjected to contrasting anthropogenic pressures (long-term mining impacts, seasonal water withdrawals), and derived Pareto-optimal solutions to disentangle the additional insights provided by isotope-aided calibration compared with streamflow alone.

The results demonstrate that strong trade-offs between isotopes and streamflow in calibrations arise in such anthropogenically-impacted catchments, where unquantified epistemic errors in streamflow observations caused by human activities compromise model reliability. Notably, discharge-only based calibrations could mis-represent runoff partitioning processes, especially in catchments with water withdrawals for irrigation, while isotopes helped identify implausible simulations by more realistic process representation. The four study catchments were ET dominated, and groundwater contributions to runoff were site specific. For example, Vetschauer displayed the most dynamic vertical fluxes, with groundwater storage fluctuations similar to soil storage in magnitude in the water balance, while Wudritz and Dobra showed

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minor groundwater contributions, consistent with the long-term mining effects. Isotope fractionation was very sensitive to the proportion of surface water area, and the absence of parameterising intermittent restored mining lakes in catchments resulted in worse results in ET partitioning processes. Further, isotopes help to disentangle ET partitioning, even if strong trade-offs in calibrations between streamflow and isotopes occurred.

This study highlights how unaccounted anthropogenic activities can alter model interpretations and underscores the complementary role of isotopes and TAMs in refining simulations under complex human-environment interactions, although only seasonally sampled isotopes were employed. While distinct trade-offs between streamflow and isotopes were observed in the study catchments, with Pareto-optimal solutions (e.g., Berste) failing to meet acceptable performance thresholds, these simulations still offer informative insights into ecohydrological dynamics and partitioning in heavily impacted catchments, even when quantitative process evaluation remains challenging. In catchments subject to intensive anthropogenic interventions (e.g., altered water distribution via irrigation or withdrawals), the severity of streamflow-isotope conflicts and compromises in TAM may serve as an indirect diagnostic of human impacts on water partitioning. Representing anthropogenic effects in ecohydrological models is inherently difficult, particularly when historical data on water use or management practices are sparse. However, we demonstrated here that TAMs are still very valuable in such applications.

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https://doi.org/10.5194/egusphere-2025-2166
Preprint. Discussion started: 5 June 2025

Reference:

Ala-Aho, P., Tetzlaff, D., McNamara, J.P., Laudon, H., Soulsby, C., 2017. Using isotopes to constrain water flux and age estimates in snow-influenced catchments using the STARR (Spatially distributed Tracer-Aided Rainfall-Runoff) model. Hydrol. Earth Syst. Sci. 21, 5089–5110. https://doi.org/10.5194/hess-21-5089-2017

Arndt, S., Heiland, S., 2024. Current status of water-related planning for climate change adaptation in the Spree River basin, Germany. https://doi.org/10.5194/nhess-2024-59

Beven, K., 2006. A manifesto for the equifinality thesis. J. Hydrol. 320, 18–36. https://doi.org/10.1016/j.jhydrol.2005.07.007

Birkel, C., Soulsby, C., 2015. Advancing tracer-aided rainfall-runoff modelling: A review of progress, problems and unrealised potential. Hydrol. Process. 29, 5227–5240. https://doi.org/10.1002/hyp.10594

Birkel, C., Soulsby, C., Tetzlaff, D., 2011. Modelling catchment-scale water storage dynamics: Reconciling dynamic storage with tracer-inferred passive storage. Hydrol. Process. 25, 3924–3936. https://doi.org/10.1002/hyp.8201

Blank, J., Deb, K., 2020. Pymoo: Multi-Objective Optimization in Python. IEEE Access 8, 89497–89509. https://doi.org/10.1109/ACCESS.2020.2990567

Bowen, G.J., Revenaugh, J., 2003. Interpolating the isotopic composition of modern meteoric precipitation. Water Resour. Res. 39, 1–13. https://doi.org/10.1029/2003WR002086

Cao, R., Huang, H., Wu, G., Han, D., Jiang, Z., Di, K., Hu, Z., 2022. Spatiotemporal variations in the ratio of transpiration to evapotranspiration and its controlling factors across terrestrial biomes. Agric. For. Meteorol. 321, 108984. https://doi.org/10.1016/j.agrformet.2022.108984

Chakraborty, S., Belekar, A.R., Datye, A., Sinha, N., 2018. Isotopic study of intraseasonal variations of plant transpiration: An alternative means to characterise the dry phases of

https://doi.org/10.5194/egusphere-2025-2166
Preprint. Discussion started: 5 June 2025

monsoon. Sci. Rep. 8, 1–11. https://doi.org/10.1038/s41598-018-26965-6

Chen, K., Tetzlaff, D., Goldhammer, T., Freymueller, J., Wu, S., Andrew Smith, A., Schmidt, A., Liu, G., Venohr, M., Soulsby, C., 2023. Synoptic water isotope surveys to understand the hydrology of large intensively managed catchments. J. Hydrol. 623, 129817. https://doi.org/10.1016/j.jhydrol.2023.129817

Chow, V. Te, 1959. Open-channel hydraulics, Erlangga : Bandung. McGraw-Hill civil engineering series Civil.

Correa, A., Birkel, C., Gutierrez, J., Dehaspe, J., Durán-Quesada, A.M., Soulsby, C., Sánchez-Murillo, R., 2020. Modelling non-stationary water ages in a tropical rainforest: A preliminary spatially distributed assessment. Hydrol. Process. 34, 4776–4793. https://doi.org/10.1002/hyp.13925

Craig, H., Gordon, L.I., 1965. Isotopic oceanography: deuterium and oxygen-18 variation in the ocean and the marin atmosphere, in: Stable Isotopes in Oceanographic Studies and Paleotemperatures. Laboratorio di Geologia Nucleare, Pisa.

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans. Evol. Comput. 6, 182–197. https://doi.org/10.1109/4235.996017

Dehaspe, J., Birkel, C., Tetzlaff, D., Sánchez-Murillo, R., Durán-Quesada, A.M., Soulsby, C., 2018. Spatially distributed tracer-aided modelling to explore water and isotope transport, storage and mixing in a pristine, humid tropical catchment. Hydrol. Process. 32, 3206–3224. https://doi.org/10.1002/hyp.13258

Deutsher Wetterdienst (DWD), 2024. Daily station observations (temperature, pressure, precipitation, sunshine duration, etc.) for Germany. URL https://cdc.dwd.de/portal/ (accessed 5.25.24).

Efstratiadis, A., Koutsoyiannis, D., 2010. One decade of multi-objective calibration approaches

https://doi.org/10.5194/egusphere-2025-2166
Preprint. Discussion started: 5 June 2025

in hydrological modelling : a review 6667. https://doi.org/10.1080/02626660903526292

Fatichi, S., Vivoni, E.R., Ogden, F.L., Ivanov, V.Y., Mirus, B., Gochis, D., Downer, C.W., Camporese, M., Davison, J.H., Ebel, B., Jones, N., Kim, J., Mascaro, G., Niswonger, R., Restrepo, P., Rigon, R., Shen, C., Sulis, M., Tarboton, D., 2016. An overview of current applications, challenges, and future trends in distributed process-based models in hydrology. J. Hydrol. 537, 45–60. https://doi.org/10.1016/j.jhydrol.2016.03.026

Fenicia, F., McDonnell, J.J., Savenije, H.H.G., 2008. Learning from model improvement: On the contribution of complementary data to process understanding. Water Resour. Res. 44, 1–13. https://doi.org/10.1029/2007WR006386

Gibson, J.J., Edwards, T.W.D., 2002. Regional water balance trends and evaporation-transpiration partitioning from a stable isotope survey of lakes in northern Canada. Global Biogeochem. Cycles 16, 10-1-10–14. https://doi.org/10.1029/2001gb001839

Godsey, S. E., W. Aas, T. A. Clair, et al. 2010. "Generality of Fractal 1/f Scaling in Catchment Tracer Time Series, and Its Implications for Catchment Travel Time Distributions." Hydrological Processes 24, no. 12: 1660–1671. https:// doi. org/ 10. 1002/ hyp. 7677.

Guevara-Escobar, A., Gonzalez-Sosa, E., Ramos-Salinas, M., Hernandez-Delgado, G.D., 2007. Experimental analysis of drainage and water storage of litter layers. Hydrol. Earth Syst. Sci. 11, 1703–1716. https://doi.org/10.5194/hess-11-1703-2007

Gupta, H.V., Sorooshian, S., Yapo, P.O., 1998. Toward improved calibration of hydrologic models: Multiple and noncommensurable measures of information. Water Resour. Res. 34, 751–763. https://doi.org/10.1029/97WR03495

Herrera, P.A., Marazuela, M.A., Hofmann, T., 2022. Parameter estimation and uncertainty analysis in hydrological modeling. Wiley Interdiscip. Rev. Water 9, 1–23. https://doi.org/10.1002/wat2.1569

Hodson, T.O., 2022. Root-mean-square error (RMSE) or mean absolute error (MAE): when to

https://doi.org/10.5194/egusphere-2025-2166
Preprint. Discussion started: 5 June 2025

use them or not. Geosci. Model Dev. 15, 5481–5487. https://doi.org/10.5194/gmd-15-5481-2022

Holmes, T., Stadnyk, T.A., Kim, S.J., Asadzadeh, M., 2020. Regional Calibration With Isotope Tracers Using a Spatially Distributed Model : A Comparison of Methods. Water Resour. Res. 56. https://doi.org/10.1029/2020WR027447

Hrachowitz, M., Savenije, H.H.G., Blöschl, G., McDonnell, J.J., Sivapalan, M., Pomeroy, J.W., Arheimer, B., Blume, T., Clark, M.P., Ehret, U., Fenicia, F., Freer, J.E., Gelfan, A., Gupta, H. V., Hughes, D.A., Hut, R.W., Montanari, A., Pande, S., Tetzlaff, D., Troch, P.A., Uhlenbrook, S., Wagener, T., Winsemius, H.C., Woods, R.A., Zehe, E., Cudennec, C., 2013. A decade of Predictions in Ungauged Basins (PUB)-a review. Hydrol. Sci. J. 58, 1198–1255. https://doi.org/10.1080/02626667.2013.803183

Iorgulescu, I., Beven, K.J., Musy, A., 2007. Flow, mixing, and displacement in using a data-based hydrochemical model to predict conservative tracer data. Water Resour. Res. 43, 1–12. https://doi.org/10.1029/2005WR004019

Jung, H., Tetzlaff, D., Birkel, C., Soulsby, C., 2025. Recent Developments and Emerging Challenges in Tracer-Aided Modeling. WIREs Water 12. https://doi.org/10.1002/wat2.70015

Karssenberg, D., Schmitz, O., Salamon, P., de Jong, K., Bierkens, M.F.P., 2010. A software framework for construction of process-based stochastic spatio-temporal models and data assimilation. Environ. Model. Softw. 25, 489–502. https://doi.org/10.1016/j.envsoft.2009.10.004

Kirchner, J.W., 2006. Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. Water Resour. Res. 42, 1–5. https://doi.org/10.1029/2005WR004362

Kirchner, J.W., 2003. A double paradox in catchment hydrology and geochemistry. Hydrol.

https://doi.org/10.5194/egusphere-2025-2166
Preprint. Discussion started: 5 June 2025

Process. 17, 871–874. https://doi.org/10.1002/hyp.5108

Klaus, J., McDonnell, J.J., 2013. Hydrograph separation using stable isotopes: Review and evaluation. J. Hydrol. 505, 47–64. https://doi.org/10.1016/j.jhydrol.2013.09.006

Kröcher, J., Ghazaryan, G., Lischeid, G., 2025. Unravelling Regional Water Balance Dynamics in Anthropogenically Shaped Lowlands: A Data-Driven Approach. Hydrol. Process. 39, 1–17. https://doi.org/10.1002/hyp.70053

Kuppel, S., Tetzlaff, D., Maneta, M.P., Soulsby, C., 2018. What can we learn from multi-data calibration of a process-based ecohydrological model? Environ. Model. Softw. 101, 301–316. https://doi.org/10.1016/j.envsoft.2018.01.001

Landesregierung Brandenburg, 2024. Landesamt für Umwelt Brandenburg (LfU). URL https://lfu.brandenburg.de/lfu/de/ (accessed 5.25.24).

Landgraf, J., Tetzlaff, D., Birkel, C., Stevenson, J.L., Soulsby, C., 2023. Assessing land use effects on ecohydrological partitioning in the critical zone through isotope-aided modelling. Earth Surf. Process. Landforms 48, 3199–3219. https://doi.org/10.1002/esp.5691

Lindström, G., Johansson, B., Persson, M., Gardelin, M., Bergström, S., 1997. Development and test of the distributed HBV-96 hydrological model. J. Hydrol. 201, 272–288. https://doi.org/10.1016/S0022-1694(97)00041-3

Liu, J., Liu, X., Wang, Y., Li, Y., Jiang, Y., Fu, Y., Wu, Y.J.Á.Y.F.Á.J., 2020. Landscape composition or configuration : which contributes more to catchment hydrological flows and variations ? Landsc. Ecol. 35, 1531–1551. https://doi.org/10.1007/s10980-020-01035-3

Luo, S., Tetzlaff, D., Smith, A., Soulsby, C., 2024. Assessing impacts of alternative land use strategies on water partitioning, storage and ages in drought-sensitive lowland catchments using tracer-aided ecohydrological modelling. Hydrol. Process. 38, 1–21.

https://doi.org/10.5194/egusphere-2025-2166
Preprint. Discussion started: 5 June 2025

https://doi.org/10.1002/hyp.15126

Manikanta, V., Vema, V.K., 2022. Formulation of Wavelet Based Multi-Scale Multi-Objective Performance Evaluation (WMMPE) Metric for Improved Calibration of Hydrological Models. Water Resour. Res. 58, 1–20. https://doi.org/10.1029/2020WR029355

Marx, C., Tetzlaff, D., Hinkelmann, R., Soulsby, C., 2021. Isotope hydrology and water sources in a heavily urbanized stream. Hydrol. Process. 35, 1–20. https://doi.org/10.1002/hyp.14377

McDonnell, J.J., Beven, K., 2014. Debates - The future of hydrological sciences: A (common) path forward? A call to action aimed at understanding velocities, celerities and residence time distributions of the headwater hydrograph. Water Resour. Res. 50, 5342–5350. https://doi.org/10.1002/2013WR015141

McDonnell, J.J., Sivapalan, M., Vaché, K., Dunn, S., Grant, G., Haggerty, R., Hinz, C., Hooper, R., Kirchner, J., Roderick, M.L., Selker, J., Weiler, M., 2007. Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology. Water Resour. Res. 43, 1–6. https://doi.org/10.1029/2006WR005467

Morris, M.D., 1991. Factorial sampling plans for preliminary computational experiments. Technometrics 33, 161–174.

Oerter, E.J., Bowen, G.J., 2019. Spatio-temporal heterogeneity in soil water stable isotopic composition and its ecohydrologic implications in semiarid ecosystems. Hydrol. Process. 33, 1724–1738. https://doi.org/10.1002/hyp.13434

Oliveira, A.M., Fleischmann, A.S., Paiva, R.C.D., 2021a. On the contribution of remote sensing-based calibration to model hydrological and hydraulic processes in tropical regions. J. Hydrol. 597, 126184. https://doi.org/10.1016/j.jhydrol.2021.126184

Paul-Limoges, E., Revill, A., Maier, R., Buchmann, N., Damm, A., 2022. Insights for the Partitioning of Ecosystem Evaporation and Transpiration in Short-Statured Croplands. J.

https://doi.org/10.5194/egusphere-2025-2166
Preprint. Discussion started: 5 June 2025

907 Geophys. Res. Biogeosciences 127, 1–19. https://doi.org/10.1029/2021JG006760
908 Pianosi, F., Sarrazin, F., Wagener, T., 2015. A Matlab toolbox for Global Sensitivity Analysis.
909 Environ. Model. Softw. 70, 80–85. https://doi.org/10.1016/j.envsoft.2015.04.009
910 Pohle, I., Koch, H., Grünewald, U., 2012. Potential climate change impacts on the water
911 balance of subcatchments of the River Spree, Germany. Adv. Geosci. 32, 49–53.
912 https://doi.org/10.5194/adgeo-32-49-2012
913 Pusch, M., Andersen, H.E., Behrendt, H., Tor, M., Hoffmann, C.C., Kronvang, B., Pedersen,
914 M.L., Tor, M., Wolter, C., 2009. Rivers of the Central European Highlands and Plains
915 525–576. https://doi.org/10.1016/B978-0-12-369449-2.00014-X
916 Pusch, M., Hoffmann, A., 2000. Conservation concept for a river ecosystem (River Spree,
917 Germany) impacted by flow abstraction in a large post-mining area. Landsc. Urban Plan.
918 51, 165–176. https://doi.org/10.1016/S0169-2046(00)00107-9
919 Rutter, A.J., Kershaw, K.A., Robins, P.C., Morton, A.J., 1972. A predictive Model of Rainfall
920 Interception in Forests. Agric. Meteorol. 9, 367–384.
921 Schlesinger, W.H., Jasechko, S., 2014. Transpiration in the global water cycle. Agric. For.
922 Meteorol. 189–190, 115–117. https://doi.org/10.1016/j.agrformet.2014.01.011
923 Scudeler, C., Pangle, L., Pasetto, D., Niu, G.Y., Volkmann, T., Paniconi, C., Putti, M., Troch,
924 P., 2016. Multiresponse modeling of variably saturated flow and isotope tracer transport
925 for a hillslope experiment at the Landscape Evolution Observatory. Hydrol. Earth Syst.
926 Sci. 20, 4061–4078. https://doi.org/10.5194/hess-20-4061-2016
927 Seibert, J., Vis, M.J.P., 2012. Teaching hydrological modeling with a user-friendly catchment-
928 runoff-model software package. Hydrol. Earth Syst. Sci. 16, 3315–3325.
929 https://doi.org/10.5194/hess-16-3315-2012
930 Shah, S., Duan, Z., Song, X., Li, R., Mao, H., Liu, J., Ma, T., Wang, M., 2021. Evaluating the
931 added value of multi-variable calibration of SWAT with remotely sensed

https://doi.org/10.5194/egusphere-2025-2166
Preprint. Discussion started: 5 June 2025

evapotranspiration data for improving hydrological modeling. J. Hydrol. 603, 127046. https://doi.org/10.1016/j.jhydrol.2021.127046

Shen, H., Tolson, B.A., Mai, J., 2022. Time to Update the Split-Sample Approach in Hydrological Model Calibration. Water Resour. Res. 58, 1–26. https://doi.org/10.1029/2021WR031523

Simůnek, J., Sejna, M., Saito, H., van Genuchten, M.T., 2013. The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media. Dep. Environ. Sci. Calif. RIVERSIDERIVERSIDE, Calif.

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. Hydrol. Earth Syst. Sci. 25, 2239–2259. https://doi.org/10.5194/hess-25-2239-2021

Smith, A.A., 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 Resour. Res. 58. https://doi.org/10.1029/2021WR030584

Soulsby, C., Birkel, C., Geris, J., Dick, J., Tunaley, C., Tetzlaff, D., 2015. Stream water age distributions controlled by storage dynamics and nonlinear hydrologic connectivity: Modeling with high-resolution isotope data. Water Resour. Res. 51, 7759–7776. https://doi.org/10.1002/2015WR017888

Sprenger, M., Tetzlaff, D., Soulsby, C., 2017. Soil water stable isotopes reveal evaporation dynamics at the soil-plant-atmosphere interface of the critical zone. Hydrol. Earth Syst. Sci. 21, 3839–3856. https://doi.org/10.5194/hess-21-3839-2017

Sprenger, M., Volkmann, T.H.M., Blume, T., Weiler, M., 2015. Estimating flow and transport

https://doi.org/10.5194/egusphere-2025-2166
Preprint. Discussion started: 5 June 2025

parameters in the unsaturated zone 2617–2635. https://doi.org/10.5194/hess-19-2617-2015

Stevenson, J.L., Birkel, C., Comte, J.C., Tetzlaff, D., Marx, C., Neill, A., Maneta, M., Boll, J., Soulsby, C., 2023. Quantifying heterogeneity in ecohydrological partitioning in urban green spaces through the integration of empirical and modelling approaches. Environ. Monit. Assess. 195. https://doi.org/10.1007/s10661-023-11055-6

Sun, W., Wang, Y., Wang, G., Cui, X., Yu, J., Zuo, D., Xu, Z., 2017. Physically based distributed hydrological model calibration based on a short period of streamflow data: case studies in four Chinese basins. Hydrol. Earth Syst. Sci. 21, 251–265. https://doi.org/10.5194/hess-21-251-2017

van der Sande, C.J., de Jong, S.M., de Roo, A.P.J., 2003. A segmentation and classification approach of IKONOS-2 imagery for land cover mapping to assist flood risk and flood damage assessment. Int. J. Appl. Earth Obs. Geoinf. 4, 217–229. https://doi.org/10.1016/S0303-2434(03)00003-5

van Huijgevoort, M.H.J., Tetzlaff, D., Sutanudjaja, E.H., Soulsby, C., 2016. Using high resolution tracer data to constrain water storage, flux and age estimates in a spatially distributed rainfall-runoff model. Hydrol. Process. 30, 4761–4778. https://doi.org/10.1002/hyp.10902

Von Hoyningen-Huene, J., 1981. Die Interzeption des Niederschlages inlandwirtschaftlichen Pflanzenbestanden. Arbeitsbericht DeutscherVerband fuer Wasserwirtschaft und Kulturbau, Schriftenr. dtsch. verb. wasserwirtsch. kulturbau, hamburg berlin. DVWK, Braunschweig, Germany. https://doi.org/10.1007/978-3-642-41714-6_91316

Wada, Y., Bierkens, M.F.P., De Roo, A., Dirmeyer, P.A., Famiglietti, J.S., Hanasaki, N., Konar, M., Liu, J., Schmied, H.M., Oki, T., Pokhrel, Y., Sivapalan, M., Troy, T.J., Van Dijk, A.I.J.M., Van Emmerik, T., Van Huijgevoort, M.H.J., Van Lanen, H.A.J., Vörösmarty,

https://doi.org/10.5194/egusphere-2025-2166
Preprint. Discussion started: 5 June 2025

C.J., Wanders, N., Wheater, H., 2017. Human-water interface in hydrological modelling: Current status and future directions. Hydrol. Earth Syst. Sci. 21, 4169–4193. https://doi.org/10.5194/hess-21-4169-2017

Wanders, N., Bierkens, M.F.P., de Jong, S.M., de Roo, A., Karssenberg, D., 2014. The benefits of using remotely sensed soil moisture in parameter identification of large-scale hydrological models. Water Resour. Res. 50, 6874–6891. https://doi.org/10.1002/2013WR014639

Wu, S., Tetzlaff, D., Beven, K., Soulsby, C., 2025. DREAM(LoAX): Simultaneous Calibration and Diagnosis for Tracer-Aided Ecohydrological Models Under the Equifinality Thesis. Water Resour. Res. 61. https://doi.org/10.1029/2024WR038779

Wu, S., Tetzlaff, D., Yang, X., Smith, A., Soulsby, C., 2023. Integrating Tracers and Soft Data Into Multi-Criteria Calibration: Implications From Distributed Modeling in a Riparian Wetland. Water Resour. Res. 59, 1–21. https://doi.org/10.1029/2023WR035509

Xia, C., Zuecco, G., Marchina, C., Penna, D., Borga, M., 2024. Effects of Short-Term Climate Variations on Young Water Fraction in a Small Pre-Alpine Catchment. Water Resour. Res. 60, 1–22. https://doi.org/10.1029/2023WR036245

Yang, X., Tetzlaff, D., Müller, C., Knöller, K., Borchardt, D., Soulsby, C., 2023. Upscaling Tracer-Aided Ecohydrological Modeling to Larger Catchments: Implications for Process Representation and Heterogeneity in Landscape Organization. Water Resour. Res. 59. https://doi.org/10.1029/2022WR033033

Yang, Y., Yoshimura, K., 2024. Simulation of Water Isotopes in Combustion-Derived Vapor Emissions in Winter. J. Geophys. Res. Atmos. 129. https://doi.org/10.1029/2023JD040543

Zhang, Y., Kong, D., Gan, R., Chiew, F.H.S., McVicar, T.R., Zhang, Q., Yang, Y., 2019. Coupled estimation of 500 m and 8-day resolution global evapotranspiration and gross

https://doi.org/10.5194/egusphere-2025-2166
Preprint. Discussion started: 5 June 2025

primary production in 2002–2017. Remote Sens. Environ. 222, 165–182. https://doi.org/10.1016/j.rse.2018.12.031