

1 **Enhancing process interpretation with isotopes: potential discharge-isotope trade-offs in**  
2 **ecohydrological modelling of heavily managed lowland catchments**

3  
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11  
12 **Abstract**

13 Tracer-aided modelling (TAM) can help quantify ecohydrological processes, as stable water  
14 isotopes ( $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ ) can provide complementary information beyond streamflow and help  
15 constrain equifinality. Whilst TAM has been successfully undertaken in smaller rural research  
16 (<100km<sup>2</sup>) catchments with limited anthropogenic impacts, its utility in more heavily managed  
17 catchments remains untested, particularly as isotope samples are usually unavailable. This  
18 study investigated four sub-catchments (Berste, Wudritz, Vetschauer, and Dobra) in the  
19 heavily-managed Middle Spree River basin (ca. 2800 km<sup>2</sup>), in NE Germany; a strategically  
20 vital water resource supplying drinking water to the capital of Berlin, Germany, and sustaining  
21 agricultural and industrial demands. Disentangling ecohydrological water partitioning in this  
22 evapotranspiration (ET) dominated region is complicated by heterogeneous land use, extensive  
23 hydraulic infrastructure and a long legacy of intensive management. We used the spatially  
24 distributed tracer-aided model STARR to simulate water fluxes and storage dynamics over a  
25 6-year period. Temporally coarse (seasonal) isotope data was used in calibration as well as  
26 streamflow to help constrain estimates of subsurface runoff sources and ET partitioning. In

27 most cases balanced calibrations using both isotopes and discharge increased confidence in  
28 plausible process representation in the modelling. When the trade-offs between dual calibration  
29 targets could not be reconciled, these were likely explained by anthropogenic factors that were  
30 not easily incorporated in the modelling framework. Such trade-offs therefore provide  
31 opportunities for learning about epistemic errors (e.g. un-represented water withdrawals for  
32 irrigation) that can be used to improve future models for heavily managed catchments. Our  
33 modelling framework shows the potential for informative insights from wider use of even  
34 sparse isotope data sets in tracer-aided modelling of complex, heavily managed catchments.

35

36 **Highlights:**

- 37 **1. Seasonal isotopes are valuable model constraints in managed catchments**
- 38 **2. Sparse seasonal isotope data may underestimate fractionation**
- 39 **3. Streamflow-isotope trade-offs indicate epistemic uncertainties related to**  
40 **management.**

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## 44 **1. Introduction**

45 Characterizing ecohydrological processes in sparsely monitored catchments with  
46 heterogeneous landscapes is inherently challenging due to spatially variable flow pathways and  
47 non-stationarity in rainfall inputs (Hrachowitz et al., 2013; McDonnell et al., 2007). This  
48 challenge can be even greater in catchments heavily modified by human activities, where a  
49 long and on-going history of disturbance can fundamentally alter processes and functioning  
50 (Marx et al., 2021). Distributed hydrological models are useful tools in addressing these  
51 challenges and are capable of capturing the dominant processes across spatio-temporal scales  
52 through regional parameterization (Fatichi et al., 2016). However, increasing model  
53 complexity to capture catchment heterogeneity makes it difficult to identify when models give  
54 “*the right answer for the wrong reason*” (Kirchner, 2006). In most catchments, rainfall and  
55 streamflow are the only available data for modelling. Streamflow-based calibration has  
56 therefore been the standard approach in hydrological modelling, leveraging the widespread  
57 availability of river discharge data to estimate model parameters across diverse catchments  
58 (Hrachowitz et al., 2013). However, calibration based on streamflow observations (single or  
59 multiple gauges) alone are usually insufficient to constrain hydrological model uncertainty, as  
60 certain parameters remain non-identifiable (Herrera et al., 2022). Consequently, simulations  
61 with multiple parameter sets can give equally plausible outputs, with process equifinality being  
62 a pervasive issue in model applications (Beven, 2006). Multi-criteria calibration, leveraging  
63 complementary datasets (e.g., soil moisture, ET, groundwater) in addition to streamflow, to  
64 mitigate this effect is increasingly common (He et al., 2019; Kuppel et al., 2018; Oliveira et al.,  
65 2021; Shah et al., 2021; Wu et al., 2023). However, classical hydrometric observations alone  
66 usually do not contain sufficient information to calibrate models and other observations such  
67 as isotopes are needed to improve understandings of storage and flux dynamics in catchments  
68 (Schilling et al., 2019).

69

70 Stable water isotopes ( $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ ) are proven tools that can help identify water sources, flow  
71 paths, and transit times, thus revealing process-based function in catchments (Holmes et al.,  
72 2023; Klaus and McDonnell, 2013; Sprenger et al., 2015). They are increasingly used as  
73 complementary datasets to streamflow, offering additional insights into catchment  
74 hydrological behavior that can aid model parametrization and calibration (Fenicia et al., 2008).  
75 In many cases, the integration of isotopes into the modelling process has advanced process  
76 representation, improving understandings of water partitioning and storage-flux interactions in  
77 heterogeneous landscapes (Birkel and Soulsby, 2015; Luo et al., 2024; McDonnell and Beven,  
78 2014; Smith et al., 2022). Consequently, tracer-aided models (TAMs) have been increasingly  
79 applied worldwide (Jung et al., 2025).

80

81 Almost all TAM studies show inevitable trade-offs in model performance resulting from  
82 conflicting information in the streamflow and isotopes timeseries (Birkel et al., 2015; Scudeler  
83 et al., 2016; Wu et al., 2023). Such differences can highlight errors in model structure and  
84 inappropriate process conceptualization (Beven, 2006; McDonnell et al., 2007; Wu et al., 2025).  
85 In addition, using some observations as “soft data” (i.e. qualitative information or measured  
86 data that are not used in calibration) to constrain models can alleviate some of the above issues  
87 (Efstratiadis et al., 2010; Wu et al., 2023). However, failing to rigorously evaluate trade-offs  
88 between isotopes and streamflow in calibration risks producing structurally biased results, even  
89 if models achieve seemingly acceptable objective metrics for both datasets. Explorations of  
90 how these trade-offs in multi-criteria modelling using isotopes to help better understand  
91 hydrological processes and indicating further improve models are relatively rare.

92

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

101

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

- 118 1. To assess the additional values of using seasonally-sampled isotopes in streamflow in  
119 addition to discharge in the simulation of heavily managed catchments.
- 120 2. To evaluate the contribution of isotopes in improving estimates of water flux  
121 partitioning and identifying the potential influence of unknown human management  
122 impacts.
- 123 3. Examining how management activities can bias ecohydrological models and advancing  
124 isotope-aided methods to disentangle process dynamics in human-dominated systems.

## 125 **2 Materials and Methods**

### 126 **2.1 Study catchment**

127 The Mid-Spree catchment (MSC) is located in the SE (Southeast) of Brandenburg, Germany  
128 (Figure 1). The 2806 km<sup>2</sup> sub-basin forms the middle part of the much larger Spree catchment  
129 (10105 km<sup>2</sup>), accounting for 28.6% of the entire catchment area. Within the MSC, the Spree  
130 River flows from Cottbus to Beeskow and through the Spreewald UNESCO Biosphere Reserve,  
131 which is an extensive wetland area. Climate is sub-continental with low precipitation and hot  
132 and dry summers (Pusch et al., 2009). Mean annual precipitation in the headwaters of the entire  
133 Spree catchment range from 600mm to 1000mm, decreasing to 556 mm in the MSC, making  
134 it one of the driest regions in Germany. Average monthly temperatures range between 19.3°C  
135 in summer (June to August) and 1.9°C in winter (December to February), respectively. Annual  
136 potential evapotranspiration, based on the FAO-56 Penman-Monteith equation (Deutscher  
137 Wetterdienst (DWD), 2024), reaches 726mm, making the MSC water-limited and highly  
138 susceptible to climate change.

139

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

143

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

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

151

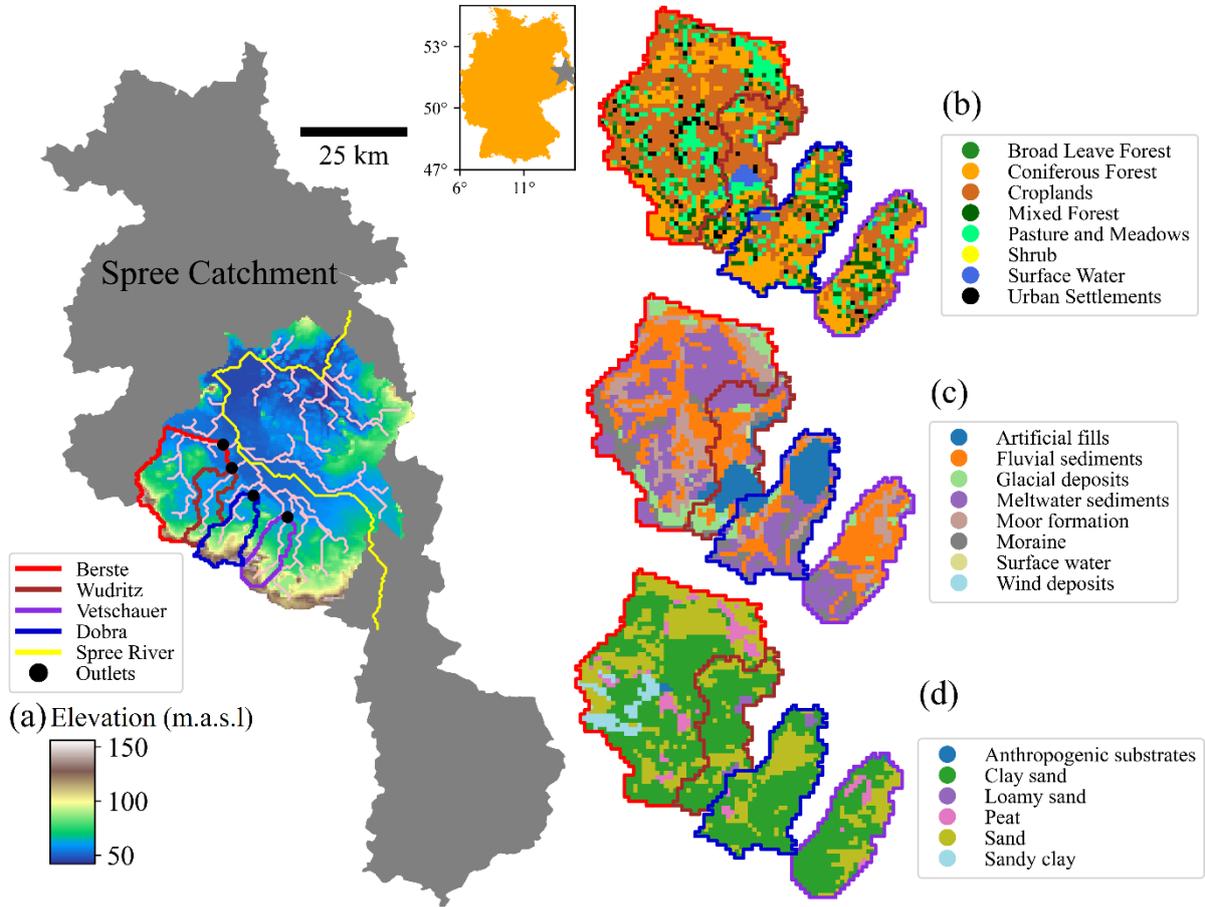
152 The geology of the sub-catchments is dominated by fluvial and meltwater sediments, especially  
153 along the river reaches, while artificial fill (from mining spoil) constitute a major part of the  
154 Wudlitz and Dobra catchments, as a result of historic lignite extraction (Landesregierung  
155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

157

158 The four sub-catchments, like much of the MSC, were influenced by intense lignite mining  
159 activities between 1960-1990 (Pusch and Hoffmann, 2000). Pumped mine water (sump water),  
160 from de-watering former open-cast mines in the Altdoberm, Schlabendorf and Seese regions  
161 was discharged to the southern tributaries of the Spree River. After the sharp decline in lignite  
162 production in the early 1990s, discharge volumes from southern tributaries in the MSC to the  
163 Spreewald are believed to be close to the pre-mining situation since 2018 (Landesregierung  
164 Brandenburg, 2024). However, more generally in the Spree catchment, the lowered  
165 groundwater table leads now to a high risk of lower river flows and water shortages in the MSC,  
166 and constitutes a threat to Berlin's water supply further downstream (Arndt and Heiland, 2024).  
167 At present, drinking water in the studied region is extracted from groundwater wells.  
168 Agricultural and industrial water withdrawals are not permitted in the Vetschauer and Dobra  
169 catchments, while this extraction from the surface water for irrigation are limited to spring and  
170 summer at the Berste and upstream area of the Wudritz catchment. The Wudritz and Dobra  
171 catchments were most severely affected by historic mining activities several decades ago, and  
172 some parts of the mined areas have been converted into small lakes, with the Wudritz catchment

173 having the largest surface water area among the four catchments. (Table 1)(Landesregierung  
 174 Brandenburg, 2024).

175



176

177 *Figure 1. (a) Elevation, river network and catchment borders, (b) land use, (c) geology, and*

178 *(d) soil types of the four sub-catchments in the MSC.*

179

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

	<b>MSC</b>	<b>Berste</b>	<b>Wudritz</b>	<b>Dobra</b>	<b>Vetschauer</b>
<b>Area (km<sup>2</sup>)</b>	2806.3	316	101.3	131.8	107.8
<b>Land use (%)</b>					
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 leaf forest	2.8	1.9	4.5	5.7	2.8
<b>Geology (%)</b>					
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
<b>Soil (%)</b>					
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

182

## 183 **2.2 The STARR model and adaptations to simulate low-relief and different land use**

184 The spatially distributed tracer-aided rainfall-runoff (STARR) model (van Huijgevoort et al.,  
 185 2016) integrates the general conceptual structure of the HBV-light hydrological model  
 186 (Lindström et al., 1997; Seibert and Vis, 2012) in a distributed, gridded framework that enables  
 187 flux tracking of water and tracers through catchments. It is operated in the PCRaster Python  
 188 framework (Karssenberget al., 2010). The STARR model includes a module for tracking of  
 189 stable water isotopes and tracer mixing (van Huijgevoort et al., 2016; Ala-aho et al., 2017). As  
 190 a fully distributed model, hydrological fluxes are simulated in each grid cell based on a simple  
 191 reservoir structure and water balance equations (Figure S1). The canopy, soil and groundwater

192 storages are each conceptualised as a single layer, with throughfall, seepage and capillary flux  
193 serving as the flow paths connecting them. The model has been successfully applied in TAMs  
194 across a range of catchments at multiple scales (0.2-2500 km<sup>2</sup>) in contrasting environments  
195 (Ala-Aho et al., 2017; Correa et al., 2020). The basic hydrological components and a brief  
196 summary of the STARR model are given in the supplementary materials (Appendix A), while  
197 van Huijgevoort et al., (2016) and (Dehaspe et al., 2018) provide more detailed descriptions.

198

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

206

207 Further, fractionation of stable water isotopes by evaporation in soil and interception storage  
208 was adapted to follow the Craig-Gordon model (Craig and Gordon, 1965), rather than being  
209 simulated by empirical representations (as in van Huijgevoort et al., 2016, Correa et al., 2020).  
210 The partitioning of evapotranspiration (ET) in the original STARR model was not applicable  
211 in the MSC as the isotopic composition of evaporation was sometimes more enriched than  
212 calculated isotopes of ambient atmospheric vapour (Chakraborty et al., 2018). Therefore, the  
213 partitioning method from HYDRUS-1D (Simůnek et al., 2013) was used here, where the  
214 transpiration originates from, and is linearly related to, soil and groundwater saturation. In  
215 order to keep parameter consistency, we adapted the interception module to the one developed  
216 in the HYDRUS-1D and the EcoPlot models (Stevenson et al., 2023), with the interception

217 volume and the maximum capacity being controlled by LAI. Channel grid cells were distinct  
218 in representing different runoff and routing processes. Roughness (Manning coefficient) used  
219 in the kinematic wave equation was defined as 0.025 in the channel grid cells as recommended  
220 in Chow (1959), while other non-channel grid cells were assigned the values similar to van der  
221 Sande et al., (2003) and according to the land use (Table S2). The channel width used in the  
222 kinematic wave equation was estimated from recent Google earth maps (03.08.2024), while  
223 the width for non-channel grid cells was defined as the grid cell size (i.e., 500 m). Other  
224 parameters were the same for all grids. Explicit parameterization of anthropogenic factors (i.e.,  
225 water withdrawals in the Berste and upper Wudritz, operation of restored lakes in Wudritz and  
226 Dobra) was excluded due to insufficient data, though the modelling results allowed these  
227 influences to be hypothesized.

228

## 229 **2.3 Data Acquisition**

### 230 2.3.1 Forcing Datasets

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

234

235 The meteorological inputs were acquired from twenty weather stations in or near the study  
236 catchments (i.e., measuring precipitation (P), temperature (T), relative humidity (RH)) and grid  
237 products of potential evapotranspiration (PET) operated by the German Weather Service  
238 (DWD) were used, and the station datasets were linearly interpolated to spatially distributed  
239 (500 m) inputs. The 8-day composite LAI dataset at 500 m resolution (MCD15A3H V6.1) was  
240 used to characterise LAI dynamics. The dataset was accessed through Google Earth Engine  
241 (GEE). The cloud masking process was based on GEE and linear resampling at daily resolution

242 was conducted, corresponding to the other input datasets. A global product to estimate the  
243 stable water isotopic composition (Interannual Monthly Mean values) of rainfall from (Bowen  
244 et al., 2005) was used and set as daily rainfall isotope input to the model constant in each month  
245 and equal to the monthly product value. This monthly value showed a consistent seasonal  
246 pattern with measurements from a rainfall station (daily resolution and aggregated to monthly  
247 values) downstream of the study area (Demnitzer Millcreek Catchment (DMC); 52°23'N, 14°  
248 15'E; Landgraf et al., 2022), indicating the representativeness of the modelled rainfall isotope  
249 input (Figure S2).

250

### 251 2.3.2 Datasets for model calibration and evaluation

252 Daily discharge from 2018 to 2023 and seasonal streamwater isotope data were collected  
253 during 2021-2023 in the outlets of the four catchments at the Bruckendorf (Berste), Ragow  
254 (Wudritz), Boblitz (Dobra), and Vetschau (Vetschauer mill creek) (Landesregierung  
255 Brandenburg, 2024). Gauging stations (Figure 1) were used for model calibration (Table 2).

256

257 Stable isotopes were sampled (via instantaneously collected “grab” sampling) every season  
258 over three years (2021, 2022, 2023) at the river outlet of the four catchments, and we used  
259 cavity ringdown spectroscopy (Picarro L-2130i, Picarro Inc, CA, USA) to analyse the ratio of  
260 the heavy stable isotopes of oxygen ( $^{18}\text{O}$ ) and hydrogen ( $^2\text{H}$ ) relative to the Vienna Standard  
261 Mean Ocean (VSMOW) (for detailed sampling and pre-process procedure refer to Chen et al.  
262 (2023)).

263

264 Further, the MODIS ET (MOD16A2GF from GEE) and PML ET (Zhang et al., 2019) 8-day  
265 composite products were compared with simulation results to evaluate evapotranspiration  
266 simulations, and qualitatively check the model performance. Despite uncertainties, the PML

267 product aligned better with flux tower (51.8922 N, 14.0337 E) records in the Spreewald (Table  
 268 2) indicating its usefulness as a comparator for modelling results (Figure S3). Groundwater  
 269 (GW) levels from 3 wells distributed in the studied region were collected (Landesregierung  
 270 Brandenburg, 2024) and the annually varying pattern of each well were used to further identify  
 271 the robustness of the model.

272

273 *Table 2. Overview of the datasets used in this study*

<b>Forcing datasets</b>	<b>Temporal resolution and period</b>	<b>Spatial resolution</b>
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
<b>Calibration datasets</b>		
Discharge	Daily; Jan 2014 - Dec 2023	4 stations
Streamwater isotopes	Seasonally; Jan 2021 - Dec 2023	4 sample locations
<b>Evaluation datasets</b>		
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
GW level	Weekly; 2019-2023	3 stations

274

275

## 276 **2.4 Model parameterisation, sensitivity analysis and calibration**

### 277 2.4.1 Model parameterisation

278 The number of calibrated model parameters was minimised and therefore some of the  
 279 parameters were assigned fixed values (Table S2). In total, 35 parameters were included for  
 280 calibration and the assigned ranges for calibration were mostly adapted from previous  
 281 applications of the STARR model, with some adjustments appropriate to the characteristics of  
 282 the study catchments (Table S2). Parameters representing soil characteristics were distributed  
 283 according to land use types (i.e., urban, water, pasture, cropland, shrub, forest) given the close  
 284 correlation between land cover and soil type in the region (see (Smith et al., 2021)). The fluxes

285 from interception to soil storage (throughfall and stemflow) are different under forest and non-  
286 forest land use, as contrasting canopy characteristics affect the rainfall partitioning (Guevara-  
287 Escobar et al., 2007), and the corresponding parameters were determined separately.

288

#### 289 2.4.2 Sensitivity analysis (SA)

290 We employed the Morris Method (Morris, 1991) to identify the most sensitive parameters. The  
291 calculation used the SAFE tool (Sensitivity Analysis for Everybody, Pianosi et al., 2015). The  
292 elementary effects (reflecting the sensitivity of each parameter) were calculated through  
293 perturbing the starting parameter by a certain variation based on a radial one-at-a-time strategy.  
294 Kling–Gupta efficiency (KGE) (Gupta et al., 2009) of simulated streamflow or stream water  
295 isotopes, corresponding to calibration scheme, was used as the objective function in calculating  
296 the elementary effects (Table 3). The Latin-Hypercube sampling method (Pianosi et al., 2015)  
297 was selected to determine the starting parameter and following perturbation. The mean  
298 elementary effect of each parameter was used to indicate the sensitivity of the corresponding  
299 parameters. Parameters related to pastures, croplands, and forests were more sensitive than  
300 others, as they cover majority of the catchment area (Table 4), and the estimated  
301 ecohydrological fluxes are mainly shown for these three land uses.

302

#### 303 2.4.3 Model calibration

304 The modified STARR model was run at daily time steps for the period from 2014 to 2023. A  
305 4-year spin-up period (2014-2017) was applied, and the remaining six years were used for  
306 calibration. The multi-objective non-dominated sorting genetic optimization algorithm II  
307 (NSGA-II) (Blank and Deb, 2020; Deb et al., 2002) was applied to derive the Pareto-optimal  
308 solutions. Five distinct calibration schemes were conducted based on measurements (i.e.,  
309 streamflow and/or stream isotopes) at the outlet of the four catchments and are detailed in Table

310 3. The first scheme (discharge-only based calibration) was calibrated only on the streamflow  
311 of all four catchments (multi-gauged streamflow calibration) using the KGE values of  
312 simulated streamflow as the objective function. Considering the potential for heterogeneity in  
313 the hydrological functioning of each catchment and to assess the additional information content  
314 of the isotope data in the modelling, calibrations (the other four schemes as in Table 3) were  
315 also carried out in each catchment independently (Scheme 2: Berste; Scheme 3: Wudritz;  
316 Scheme 4: Vetschauer; Scheme 5: Dobra) and based on KGE values of simulated streamflow  
317 and isotope (isotope-aided calibrations) (Table 3). Simulations based on NSGA-II were  
318 conducted with 80 generations and 280 individuals in the population per generation, and the  
319 first pareto front in the 80<sup>th</sup> generation were employed as the solution. Five independent  
320 calibrations were conducted for each calibration scheme to minimize potential biases. Balanced,  
321 discharge-dominated, and isotope-dominated solutions were defined in the isotope-aided  
322 calibrations (schemes 2-5), five parameter sets from each of the five independent calibrations  
323 (25 parameter sets in total) were selected for each of these three solution types. These three  
324 solution types corresponded to parameter sets in the middle (with minimum Euclidean distance  
325 to the best KGE of discharge and isotopes, i.e., (KGE\_discharge=1.0, KGE\_isotope=1.0)) and  
326 the edges of the Pareto front, respectively. In the scheme 1, only balanced solutions (minimum  
327 Euclidean distance to the best KGE point, i.e., KGE\_Berste=1.0, KGE\_Wudriz=1.0,  
328 KGE\_Vetschauer=1.0, KGE\_Dobra=1.0) were employed. The aggregated 25 parameter sets  
329 for each solution type (i.e., balanced, discharge-dominated, isotope-dominated) encompass a  
330 broad range of parameter variability and allow a robust comparison among solution types. No  
331 validation period was employed, as the present study aimed to better constrain ecohydrological  
332 processes in the MSC, rather than for forecasting applications. Also, others have argued that  
333 calibrating to the full available data and skipping model validation can be more robust than the  
334 traditional split-sample approach in hydrological modelling (Shen et al., 2022).

335

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

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

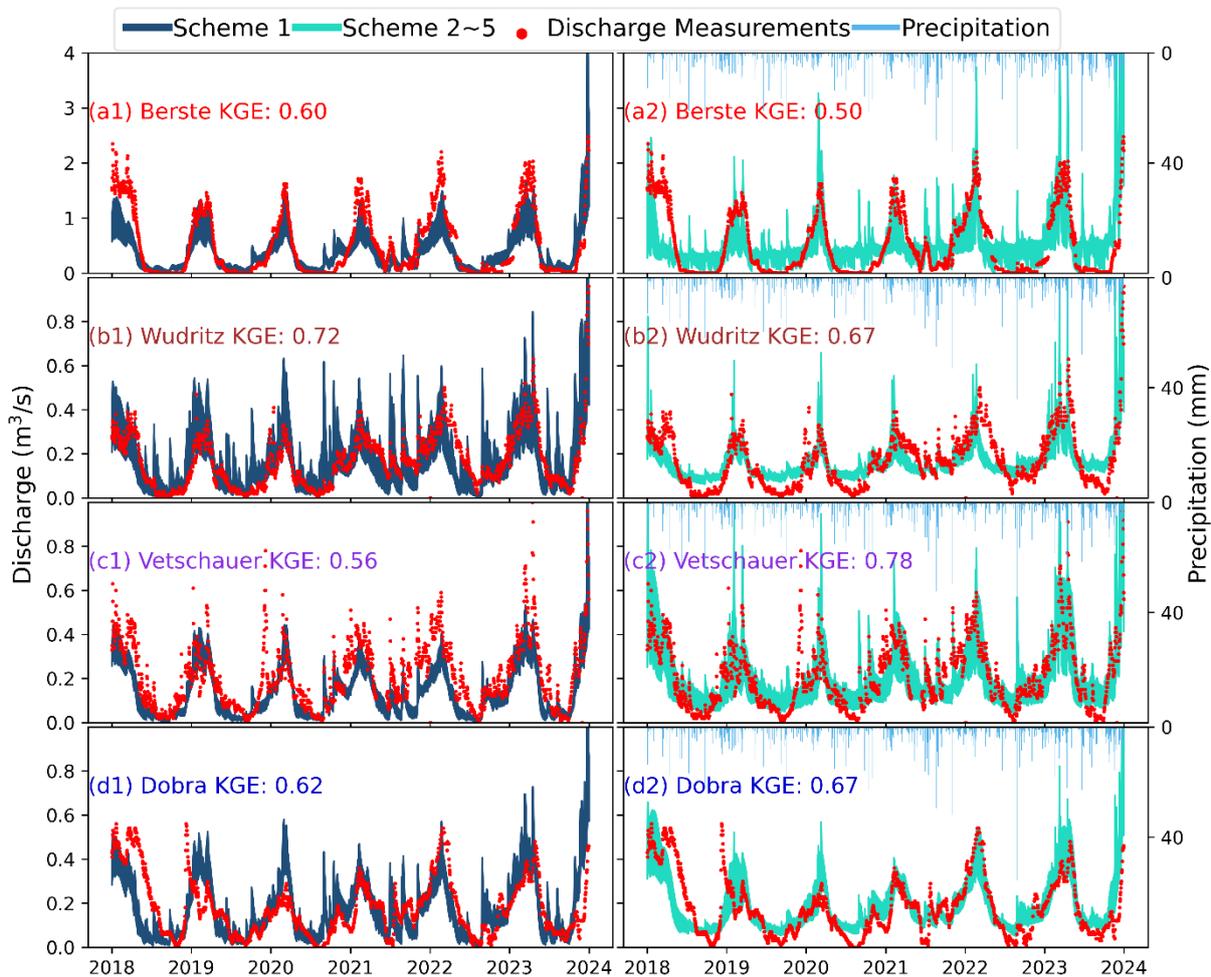
339

340 **3 Results**

341 **3.1 Model performance**

342 3.1.1 Discharge simulations

343



344

345 *Figure 2. Discharge simulations at the outlet of each catchment based on the balanced*  
346 *solutions in the calibration scheme 1 (first panel (a1, b1, c1, d1)) and schemes 2-5 (second panel*  
347 *(a2, b2, c2, d2)). (a) Berste; (b) Wudritz; (c) Vetschauer; (d) Dobra.*

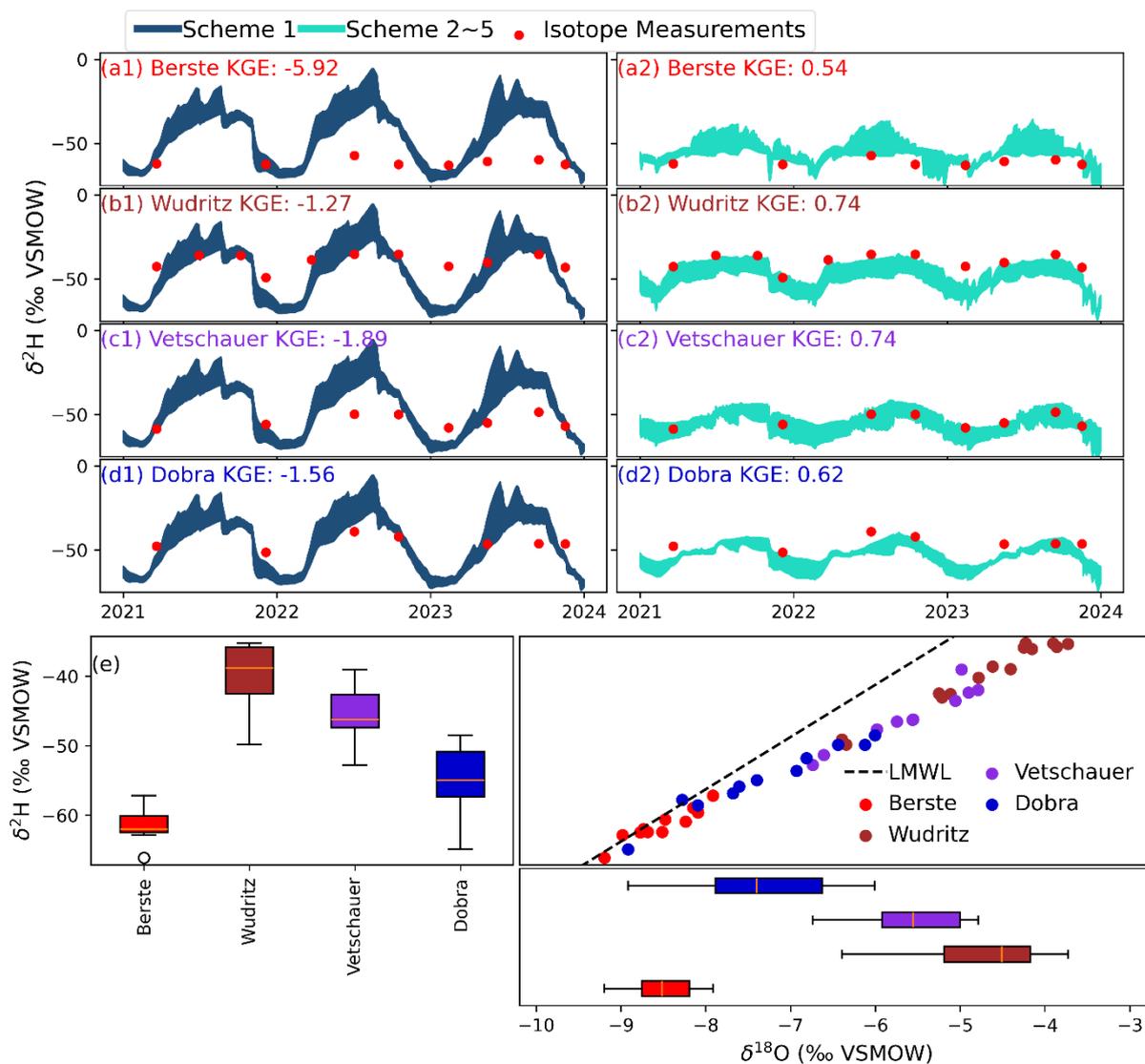
348

349 Discharge-only based calibrations (scheme 1) and the balanced solutions of the isotope-aided  
350 calibrations (schemes 2-5) successfully captured discharge dynamics in each catchment with  
351 average KGE >0.5 (Figure 2). This performance was better (KGE > ~0.8) in discharge-

352 dominated solutions of the isotope-aided calibrations (Figure S4). Contrasting flow regimes  
353 were shown in each catchment, e.g., Berste presented low base flows and Vetschauer had  
354 quicker responses to rainfall. Therefore, scheme 1 underestimated peak flow, showing the  
355 trade-offs in balancing performance across the four catchments. Trade-offs between discharge  
356 and isotopes objectives within each catchment (schemes 2-5) also led overestimated base flow  
357 (particularly in Berste and Wudritz) in the balanced solutions of schemes 2-5 (Figure 2).

358

360



361

362 *Figure 3. Stream water isotope simulations at the outlet of each catchment based on the*  
 363 *balanced solutions in the calibration scheme 1(first panel (a1, b1, c1, d1)) and schemes 2-*  
 364 *5(second panel (a2, b2, c2 d2)). (a) Berste; (b) Wudritz; (c) Vetschauer; (d) Dobra; and (e)*  
 365 *Dual isotope from Jan 2021 to Dec 2023 in each catchment.*

366

367 The stream isotope signatures in the four catchments showed contrasting characteristics (Figure  
 368 3). Overall, apart from the Berste, streamwater isotopes in each catchment plotted below the  
 369 local meteoric water line (LMWL), reflecting differences in fractionation. The similar

370 alignment of isotopes along a shared local evaporation line indicates comparable atmospheric  
371 moisture demand among the catchments (Figure 3). The Berste exhibited the most depleted  
372 isotopic signature ( $\delta^2\text{H}$ :  $\sim -62\text{‰}$ ), while Wudritz was the most enriched catchment ( $\delta^2\text{H}$ :  $\sim -$   
373  $38\text{‰}$ ), and their enrichments positively correlated with the extent of surface water area,  
374 although all catchments have low surface water coverage ( $< 8\%$ ) (Figure 3). Simulations in all  
375 solutions of each scheme reproduced the seasonal isotope dynamics, with summer enrichment  
376 and winter depletion (Figure 3; Figure S5). However, the variability of isotopes was  
377 overestimated in scheme 1 and in the discharge-dominated solutions of schemes 2-5, although  
378 mean simulations and measurements were comparable and much better performance were  
379 shown in the latter. This showed that different flow paths, mixing processes and fractionation  
380 effects in the catchments were likely unrealistic in the discharge-only based calibrations  
381 (scheme 1) or discharge-dominated solutions in isotope-aided calibrations (schemes 2-5). The  
382 balanced solutions or isotope-dominated solutions in schemes 2-5 yielded much more  
383 consistent simulations of the isotope dynamics, although this came at the cost of much poorer  
384 discharge performance (Figure 3; Figure S5).

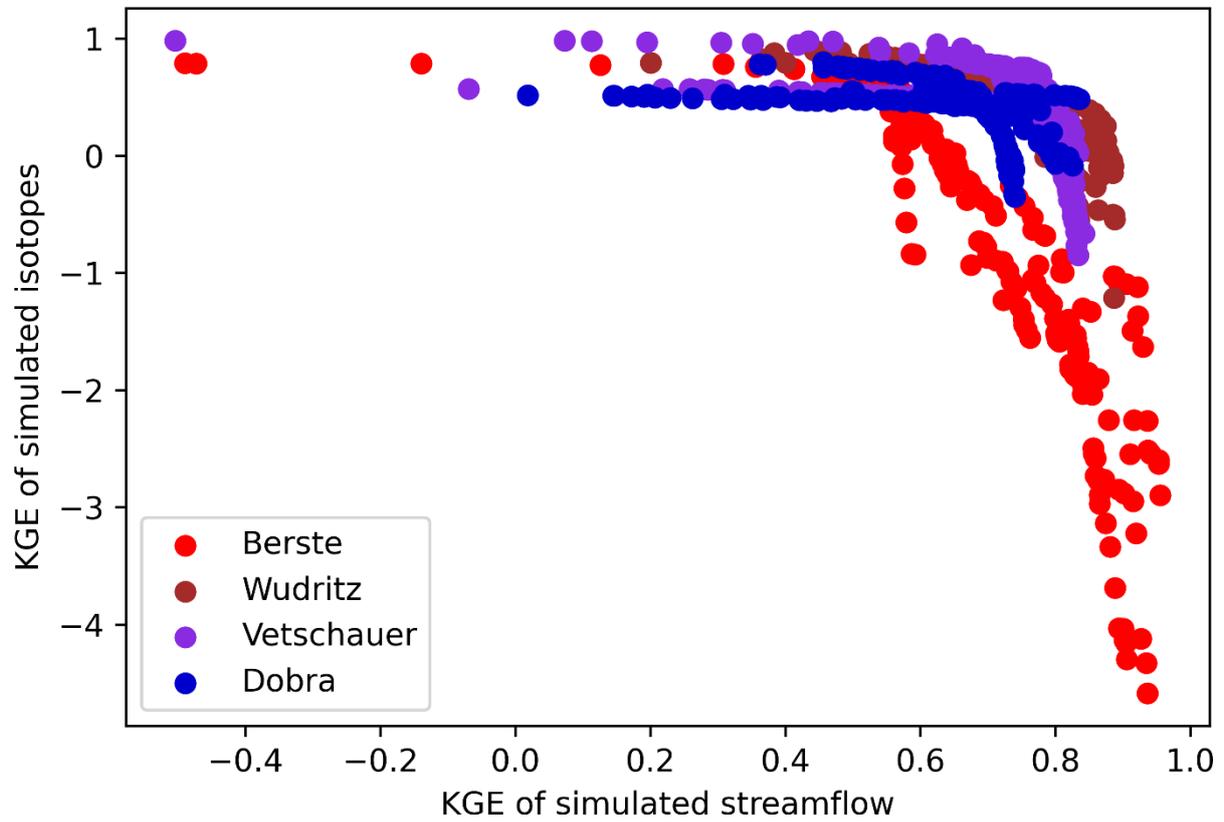
385

## 386 **3.2 Trade-offs between streamflow and isotope-based calibrations**

### 387 3.2.1 Pareto front of simulations

388 The Pareto fronts of simulations from schemes 2-5 show the range of potential solutions of  
389 streamflow and isotopes (Figure 4). Berste resulted in lower KGE of both isotopes and  
390 streamflow than the other three catchments, while the balanced trade-off solutions in  
391 Vetschauer were the most robust (Figure 4). On each Pareto front, increased KGE of simulated  
392 discharge was accompanied by a slight decrease in the KGE of simulated isotopes, until the  
393 discharge KGE reached a certain threshold, beyond which the isotope KGE dropped sharply.  
394 This threshold was approximately 0.7-0.8 at Wudritz, Vetschauer and Dobra, but only around

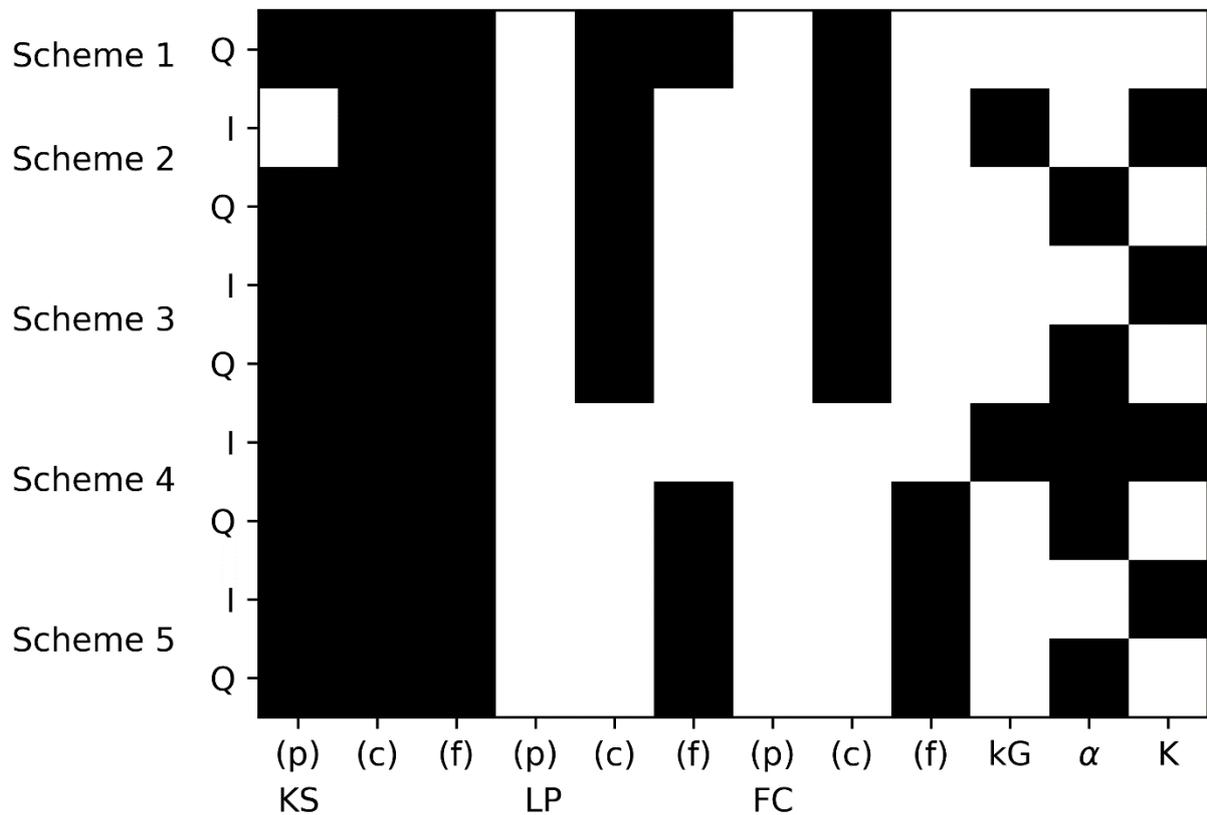
395 0.5 at Berste. This unsatisfactory performance at Berste reflected the stronger conflicting  
396 information provided by isotope and streamflow data under the existing model structure and  
397 potentially reflected unknown impacts resulting from management (see Discussion below).  
398



399

400 *Figure 4. Pareto fronts of simulations from all five independent calibrations in schemes 2-5.*

401



403

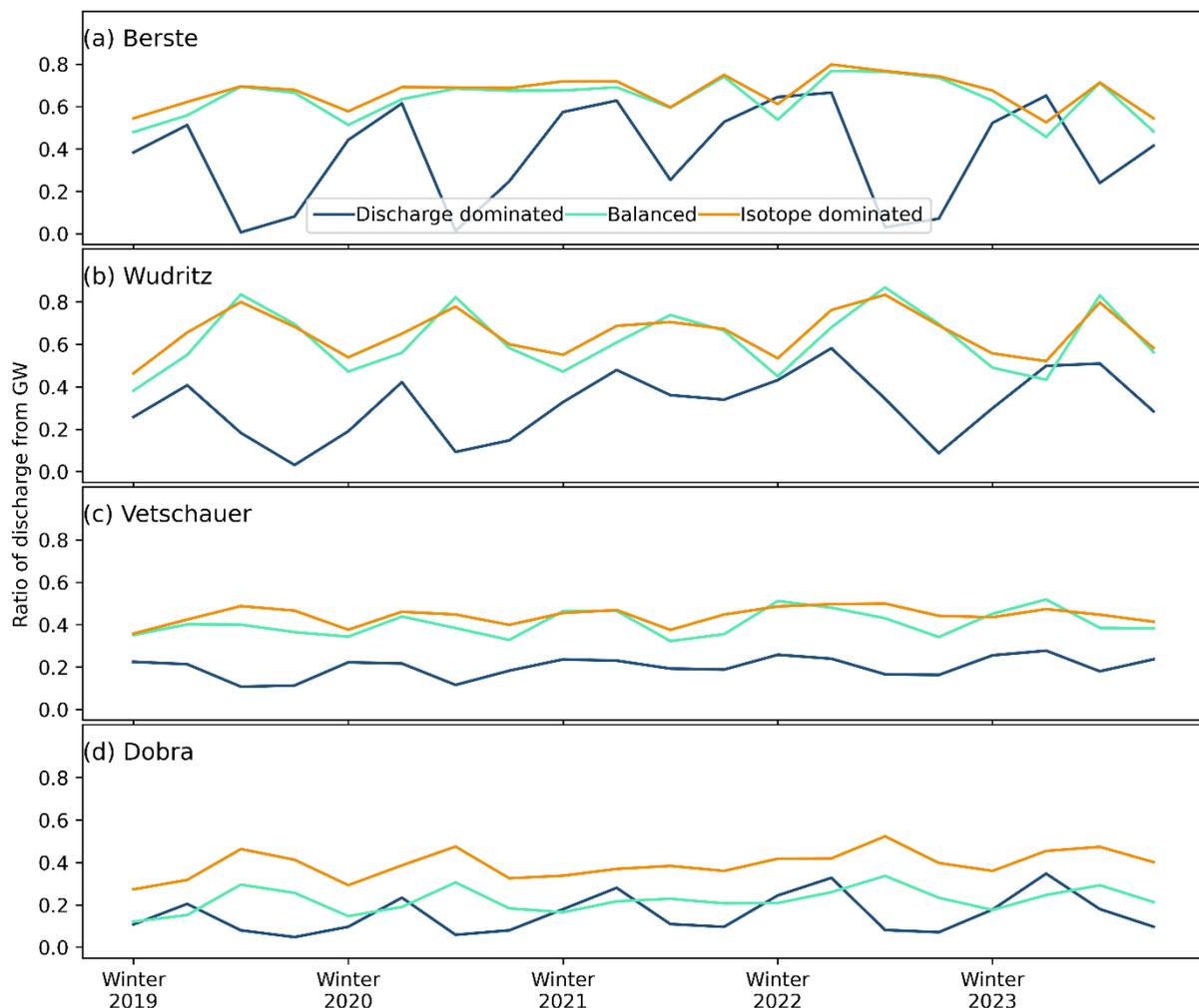
404 *Figure 5. Sensitive parameters in each calibration scheme (The top six sensitive parameters*  
 405 *are shown shaded). I and Q in the y-axis represent isotopes and discharge; (p), (c), (f) represent*  
 406 *pasture, croplands, forest, respectively. kS, kG LP,  $\alpha$ , K control processes of runoff from soil,*  
 407 *runoff from groundwater, Actual ET, interception and ET partitioning, respectively; and FC is*  
 408 *the soil water storage capacity.*

409

410 3.2.2 Impact of calibration on contributing runoff generation processes

411 Runoff generation from soil storage was the most sensitive hydrological processes in the  
 412 simulations in all calibration schemes, while groundwater (GW) contributions were highlighted  
 413 by isotopes in Berste and Vetschauer (Figure 5). Contrasting GW contributions to discharge  
 414 were shown in different solution types of the isotope-aided calibrations (Figure 6). In the  
 415 discharge-dominated solutions of schemes 2-5, runoff was mainly sourced from the shallower

416 soil stores (soil storage in the STARR), while this contribution decreased in the isotope-  
 417 dominated solutions with groundwater sources being more important (Figure 6). Summer peaks  
 418 of groundwater contribution shown in the isotope-dominated and balanced solutions aligned  
 419 better with the known hydrological regime of the local region (e.g. Ying et al., 2024), compared  
 420 to discharge-dominated solutions (Figure 6). Among the four catchments, higher groundwater  
 421 contributions were shown in Berste and Wudritz, reaching 60% in isotope-dominated or  
 422 balanced solutions (Figure 6).  
 423



424  
 425 *Figure 6. The mean ratio of seasonal runoff from groundwater storage at each catchment*  
 426 *(winter, spring, summer, fall of each year along the X-axis). The results were calculated from*  
 427 *the discharge dominated, balanced and isotope dominated solutions in schemes 2-5.*

428

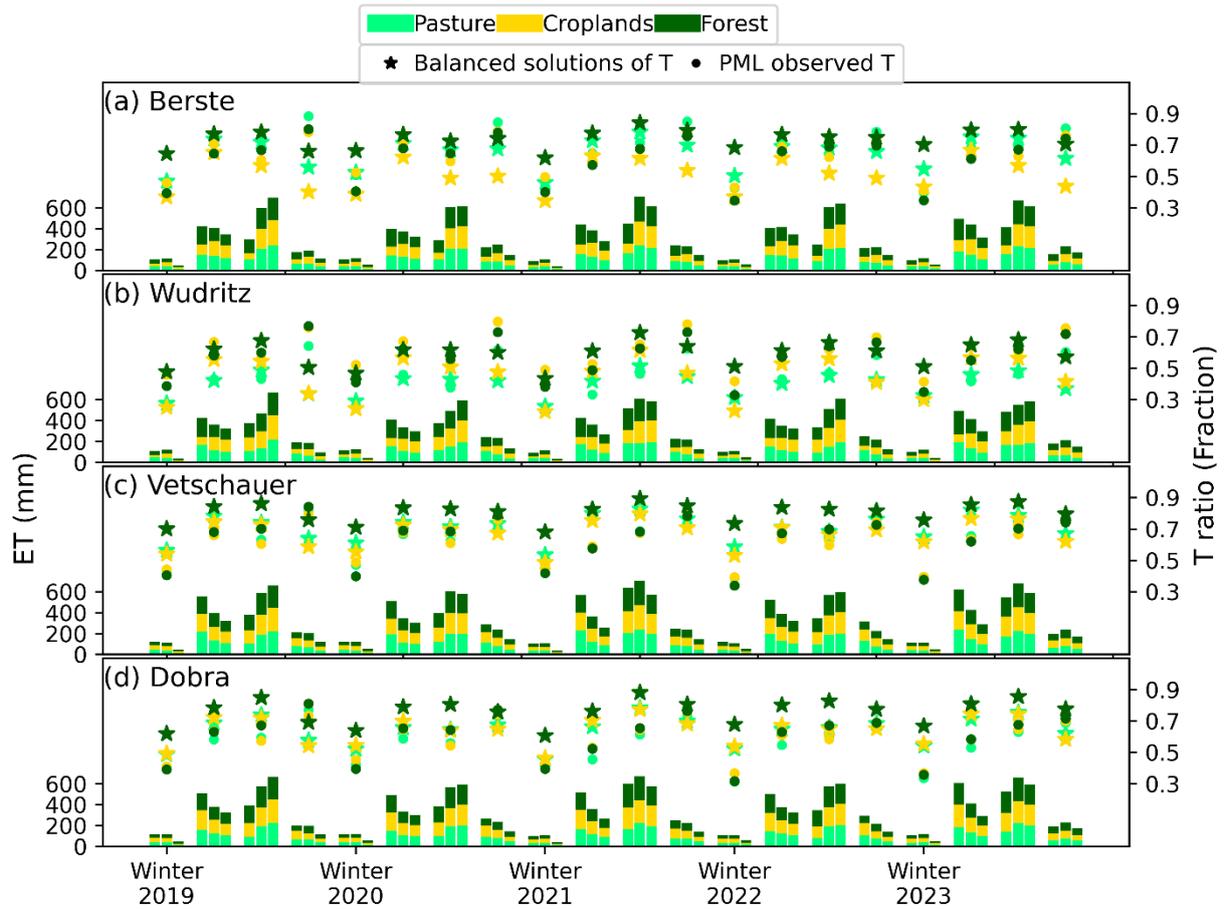
429 *Table 4. Performance metric values (KGE) of simulated spatially averaged ET in the scheme*  
430 *1 and balanced solutions of schemes 2-5 based on remote sensing products at the studied*  
431 *catchments.*

<b>Locations</b>	<b>Scheme1</b>		<b>Schemes 2-5</b>	
	<b>MODIS</b>	<b>PML</b>	<b>MODIS</b>	<b>PML</b>
Berste	0.59	0.46	0.45	0.36
Wudritz	0.59	0.45	0.78	0.59
Vetschauer	0.56	0.42	0.77	0.62
Dobra	0.56	0.44	0.77	0.64

432

### 433 3.2.3 Impact of calibration on ET estimates and ET partitioning

434 The parameters controlling the return flux of water to the atmosphere (ET) were sensitive to  
435 the use of both discharge and isotopes in calibration (Figure 5). Further, spatially averaged ET  
436 in the balanced solutions of all schemes aligned well with both remote sensing products  
437 (MODIS and PML), supporting the robustness of the calibrations, although the trade-offs  
438 between discharge and isotopes at Berste resulted in a degraded performance in the Scheme 2  
439 (Table 4). All solution types in the isotope-aided calibrations generally showed only slight  
440 differences, except for croplands in Berste and Wudritz, where the discharge-dominated  
441 solutions simulated higher ET (Figure S6). ET showed strong seasonality with peaks in spring  
442 and summer in all solution types (Figure 7; Figure S6). This was consistent with the satellite  
443 ET observations. However, balanced solutions showed higher springtime ET yet lower  
444 modelled ET in summer across all catchments compared to the remote sensed products, due to  
445 limited soil moisture. These differences decreased during wet summers (e.g., 2021 and 2023)  
446 (Figure 6; Figure S4).



447

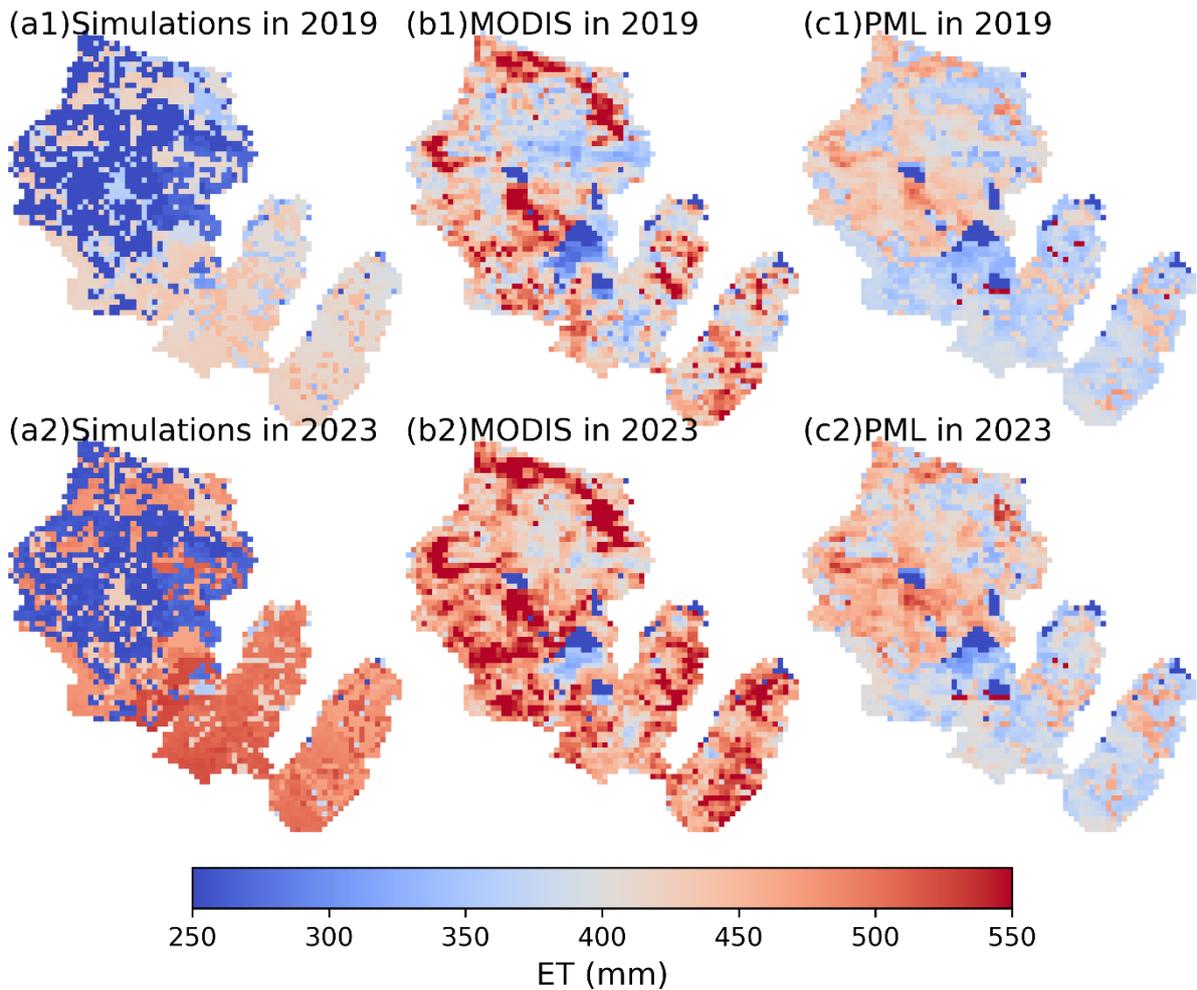
448 *Figure 7. Seasonal total ET and transpiration ratio ( $T/ET$ ) from the balanced solutions at (a)*  
 449 *Berste in scheme 2; (b) Wudritz in scheme 3; (c) Vetschauer in scheme 4; (d) Dobra in scheme*  
 450 *5, and RS products. Bars and scatters indicate ET and T ratios, respectively. Each season*  
 451 *contains three bars, ordered from left to right as follows: balanced solutions, MODIS and PML*  
 452 *ET products.*

453

454 ET in the discharge-dominated solutions of schemes 2-5 presented a relatively uniform spatial  
 455 distribution, while the balanced or isotope-dominated solutions retained more pronounced  
 456 spatial variability, aligned with the MODIS estimates (Figure 8; Figure S7). However, no  
 457 solutions successfully captured the distributions of ET in the MODIS or PML. In addition, high  
 458 ET in the PML product was more consistent with croplands distribution, which indicated the

459 potential influence of irrigation in croplands and were not shown in the MODIS, reflecting the  
460 uncertainty of accuracy of spatial distributions in these remote sensing products. (Figure 8).  
461  
462 ET partitioning (into E and T) became more sensitive for simulations constrained by isotopes  
463 as the corresponding parameters (K) ranked higher compared to Scheme 1 or discharge-  
464 dominated solutions in Schemes 2-5. This is consistent with the importance of fractionation in  
465 the variation of isotopes (Figure 5). In all catchments, the transpiration ratio from each land  
466 use had similar temporal dynamics (summer peaks and winter troughs), and was higher in forest  
467 than in the other two land uses (Figure 7; Figure S8). Berste, Dobra and Vetschauer yielded  
468 higher transpiration ratios, with 70-80% and 40-60% in summer and winter, respectively,  
469 compared to Wudritz. Further, Wudritz was ~10% lower (compared to other catchments) in  
470 transpiration ratio, aligned well with the PML estimates. In addition, Berste and Wudritz  
471 showed contrasting performances among different type of solutions (discharge-dominated,  
472 balanced or isotope-dominated solutions), with discharge-dominated solutions showing higher  
473 ratios (Figure S8).

474



475

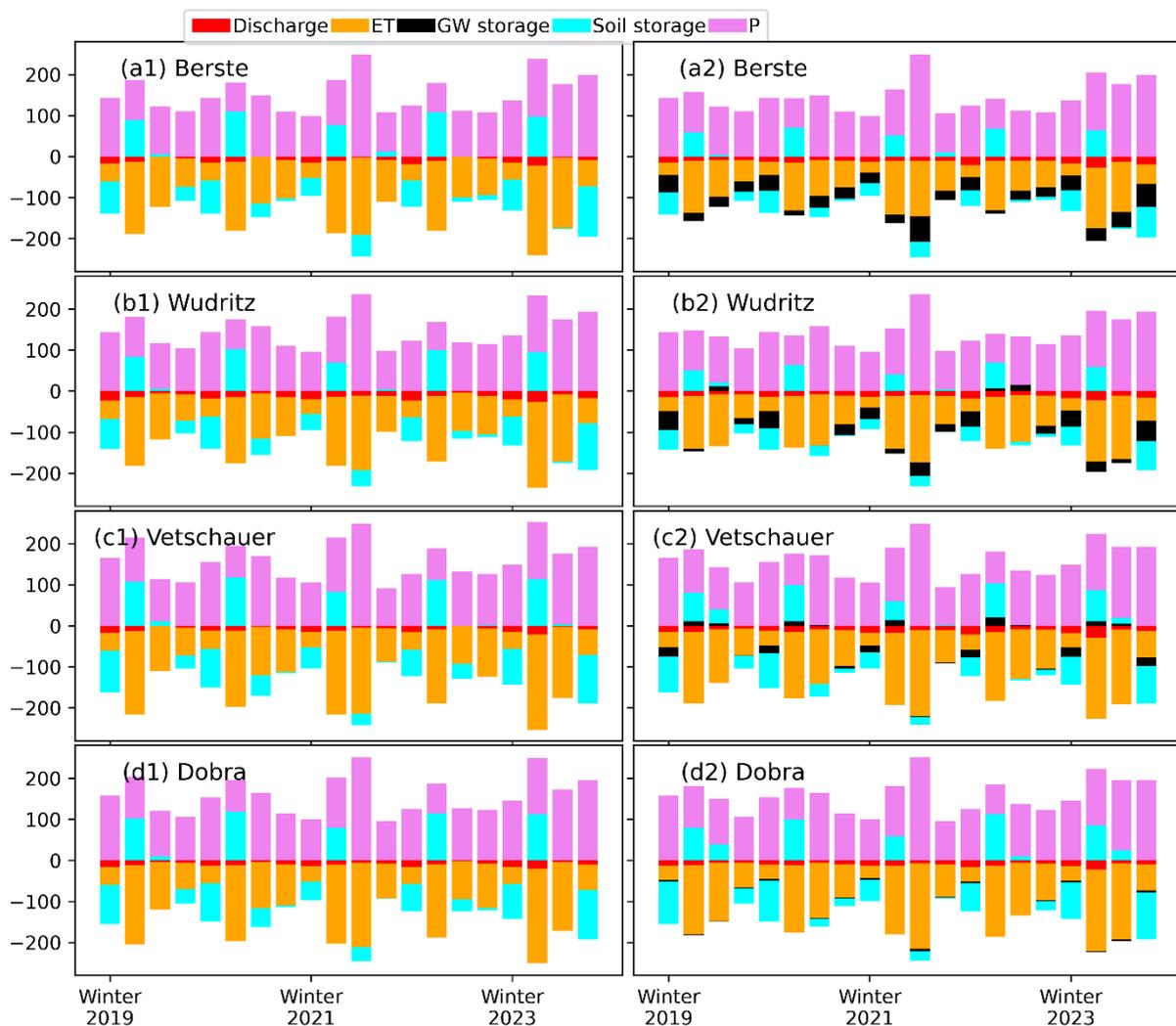
476 *Figure 8. Spatial distribution of ET in the four catchments. (a) Balanced solutions in schemes*  
 477 *2-5; (b) MODIS ET; (c) PML ET. Suffix “1” and “2” in titles of each subplot mean dry year*  
 478 *of 2019 and wet year of 2023, respectively.*

479

### 480 **3.3 Quantification of water balance components**

481 The partitioning into different water balance components was relatively consistent across all  
 482 catchments, irrespective of the calibration schemes (Figure 9). ET was the dominant output  
 483 flux, especially during the spring and summer period (> 90%). Simulations showed that soil  
 484 storage played the major role in supplying water for ET in spring and early summer and was  
 485 subsequently replenished during autumn and winter. Discharge accounted for a minor  
 486 proportion of the water balance (~5%). Variations of groundwater storage in each season were

487 small (<1% of the total water balance) in simulations calibrated on discharge alone, while it  
 488 increased to ~5 - 30% (catchment dependent) when isotopes were included in calibrations  
 489 (Figure 9). A clear seasonal pattern of groundwater dynamics was shown in Vetschauer, with  
 490 declining storage during the spring and summer and replenishment in winter and fall. In  
 491 contrast, the groundwater storage kept increasing in each season at Berste, while this storage  
 492 only occasionally decreased in summer at Wudritz and Dobra (Figure 9). The annual increased  
 493 in subsurface storage aligned with the gradually recovery of the groundwater level in this  
 494 region following the 2018-2019 drought (Figure S9).



495  
 496 *Figure 9. Seasonal water balances at (a) Berste; (b) Wudritz; (c) Vetschauer; (d) Dobra, based*  
 497 *on the balanced solutions in the calibration scheme 1(first panel (a1, b1, c1, d1)) and schemes*  
 498 *2-5(second panel (a2, b2, c2 d2)). Positive bars represent water sources, while negative bars*

499 are water losses. *“Channel storage” and “Interception storage” were too small compared to*  
500 *other components to show in the figure.*

## 501 **4 Discussion**

502 The key novelty of this study lies in evaluating the use of multi-year, seasonally sampled  
503 isotopes for calibrating a TAM to ET-dominated and heavily managed catchments. Previous  
504 catchment-scale TAM applications have generally been in smaller experimental catchments  
505 with limited human influences (Nan and Tian, 2024). Whilst such work has demonstrated the  
506 value of isotopes in constraining hydrological models, the present study has shown similar  
507 potential benefits in heavily managed regions. Furthermore, the trade-offs between using  
508 discharge and/or isotopes in model calibration showed that isotopic information can still  
509 provide valuable preliminary process insights. The observed inter-catchment differences in  
510 isotope variations were influenced by the interaction of dominant runoff sources, associated  
511 mixing processes with water storages and the effects of evaporative fractionation; capturing  
512 these in simulations were, in turn, linked to modelled discharge performance. The response of  
513 runoff to rainfall, seasonal flow variations and baseflow contribution derived from discharge-  
514 calibrated models showed inconsistency with isotope-inferred processes. Given that  
515 contrasting trade-offs were identified among catchments within the same region, these  
516 discrepancies are likely to in part reflect undocumented influences of human management and  
517 provide a potential pathway to model improvement.

518

### 519 **4.1 Benefits of incorporating isotopes into model calibration**

520 Streamflow is most widely used in hydrological model calibration due to its ready availability.  
521 Here, similar to many previous studies, streamflow dynamics and overall runoff volumes were  
522 effectively captured by discharge-only based calibrations despite the ET-dominance. However,  
523 slight overestimations of flow occurred during winter peaks, with underestimations during  
524 summer low-flows. In addition, simulated spatially averaged ET (weekly flux) aligned closely

525 with RS ET products (e.g., MODIS or PML), with  $KGE > 0.5$ . Although groundwater recharge  
526 was implausibly low, approximate partitioning of precipitation into green and blue water fluxes  
527 was accurately constrained by streamflow calibrations. Similarly, in some other literature,  
528 multi-criteria calibrations incorporating both streamflow and RS ET demonstrated marginal  
529 improvements in annual ET or streamflow simulations, compared to discharge-only based  
530 calibrations, albeit with reduced parameter equifinality (Oliveira et al., 2021; Shah et al., 2021),  
531 although in other cases they have not been beneficial. (Ala-aho et al., 2017b).

532

533 However, previous work using tracers has shown that based on calibration on streamflow alone  
534 can result in the wrong conceptualization of hydrological processes (Ala-Aho et al., 2017a; van  
535 Huijgevoort et al., 2016; McDonnell and Beven 2014). Discharge-only based calibrations  
536 normally exhibit significant uncertainty in representing internal hydrological processes, owing  
537 to high degrees of model freedom and non-identifiable parameters (Herrera et al., 2022). This  
538 was evidenced by poorly simulated isotopes under scheme 1. Moreover, catchment discharge,  
539 as an output integrating upstream hydrological processes, provides only limited insight into  
540 spatially distributed partitioning of water volumes and flow paths (Fatichi et al., 2016). This  
541 limitation becomes more pronounced as models incorporate more complex spatial  
542 disaggregation and physics-based process representations (Sun et al., 2017). A multi-gauge  
543 regional streamflow calibration, as used in Scheme 1, has been shown to improve the spatial  
544 representativeness of simulations and provides a greater constraint on relationships between  
545 catchment characteristics and streamflow dynamics (Liu et al., 2020). However, internal  
546 mixing and runoff generation processes (evidenced by isotope dynamics) under scheme 1 did  
547 not show much difference to the single-gauge calibrations (i.e., discharge-dominated solutions  
548 in schemes 2-5). Improvements on simulations of subsurface processes were also not clear in  
549 other literature (Wanders et al., 2014). Furthermore, sensitivity analysis revealed that discharge

550 was more sensitive to soil drainage process in all three major land uses (i.e., forest, croplands,  
551 pasture) of the four studied catchments, and parameters controlling other hydrological  
552 processes were less identifiable.

553

554 Incorporating stable water isotopes improved modelling of ecohydrological partitioning and  
555 storage dynamics in our study. Multi-criteria calibration using both streamflow and isotopes  
556 enables a wider exploration of the parameter space to satisfy multiple calibration objectives  
557 (Holmes et al., 2020). Subsurface processes in the deeper layer (e.g., discharge from  
558 groundwater in the present modelling) are inherently challenging to constrain using near-  
559 surface observations (e.g., ET, soil moisture), and these processes are usually poorly  
560 understood (Beven, 2006). Stable water isotopes are powerful in this regard as they integrate  
561 the cumulative effects of water flow paths and mixing across all hydrological storages (Godsey  
562 et al., 2010; Tafvizi et al., 2024). Our TAM revealed that discharge-only based calibration or  
563 discharge-dominated solutions in isotope-aided calibrations failed to capture such mixing  
564 processes, as their simulated isotopes deviated far from observations. Modelling results that  
565 reconciled simulated and observed isotopes likely better represented mixing between soil water  
566 and groundwater storage. This generally increased runoff generation from groundwater,  
567 characterized by more depleted isotopes, and modulated simulated outflow signatures,  
568 flattening the seasonal isotopic variability, and thus, giving more plausible process  
569 representation. This aligns with previous findings where dominant subsurface flows produce  
570 subtle isotopic variations (Iorgulescu et al., 2007; Oerter and Bowen, 2019) and where  
571 contrasting isotope signatures across water stores are key to disentangling water mixing  
572 processes (Kirchner, 2003).

573

574 The fractionation of stable water isotopes is governed by evaporation, and measured isotopes  
575 at the outlet reflected the aggregated influence of evaporation across the whole catchment.  
576 Parameters controlling ET processes (e.g., FC and LP) exhibited similar sensitivity to isotopes  
577 and discharge, supporting the value of isotopes as a constraint on ET dynamics in simulations.  
578 This is similar to the incorporation of remote sensed ET in calibrations found in other literatures  
579 (Oliveira et al., 2021). In addition, total seasonal ET volumes across the catchments showed  
580 minimal variations among different solution types in the Pareto front, implying that streamflow  
581 and isotopes similarly constrain bulk ET estimates. The use of relatively coarse isotopic  
582 datasets and inter-annually averaged rainfall isotope inputs in this study likely introduced some  
583 uncertainty in ET process constraints, and higher-resolution data would better capture temporal  
584 variability in fractionation intensity (Sprenger et al., 2017). Nevertheless, the results are  
585 reasonable and consistent with broader findings in the literature: while isotopic tracers are  
586 widely recognized for improving estimates of E/T partitioning (Gibson and Edwards, 2002),  
587 their utility in refining total ET quantification prior to discharge remains less clearly  
588 demonstrated, particularly at larger spatial scales.

589

590 Despite this, isotopes are still likely to provide more additional information than ET  
591 observations for constraining ET dynamics at the catchment scale. Although calibrations based  
592 on discharge and temporal patterns of spatially aggregated ET can help constrain total ET in  
593 an efficient manner (Oliveira et al., 2021; Shah et al., 2021); and spatial ET patterns have also  
594 helped improve spatial representation of ET (Dembélé et al., 2019), resolving the underlying  
595 components contributing to ET with contrasting residence times (e.g. interception, soil  
596 evaporation, transpiration etc.) remains difficult. In this regard, isotopes offer additional  
597 constraints separating the sources of individual hydrological components, as well as the  
598 capability of tracking sources of ET, as has been demonstrated in numerous previous studies

599 (Martinelli et al., 1996; Ren et al., 2019). In the present study, the dominant contribution of  
600 groundwater to streamflow inferred from the isotope-aided calibrations indicated reduced  
601 storage in the shallow subsurface layer (soil storage in STARR), which in turn leads to  
602 improved estimates of total ET and ET water sources compared to discharge-only calibrations.

603

#### 604 **4.2 Isotopic insights into water flux partitioning in managed catchments**

605 In the studied catchments, runoff was predominantly generated from groundwater and soil  
606 storage, reflecting a subsurface-process dominated flow regime. This pattern aligns with  
607 observations across much of the Spree catchment, where subsurface-driven runoff mechanisms  
608 are widespread (Chen et al., 2023). Runoff in the upper Spree catchment is predominantly  
609 groundwater-driven (Kröcher et al., 2025), a pattern consistent with the simulated performance  
610 in the studied region after incorporation of isotopes. In addition, the influence of groundwater  
611 in the studied four catchments may potentially increase, as the opencast mines have been closed  
612 for 30 years and it is unclear to whether groundwater levels have fully stabilized and how they  
613 affect each of the study catchments (Kröcher et al., 2025). The increased temperature and shift  
614 of precipitation from summer to winter due to climate change also possibly leads to increased  
615 ET during winter and spring reducing discharge and groundwater recharge accordingly. This  
616 could result in contrasting water distributions in each season, and intensifying negative climatic  
617 water balance in the local environment (Pohle et al., 2012).

618

619 The transpiration ratios in the studied region were roughly 65% in the PML estimates, which  
620 is similar to other studies in the Spree catchment (Landgraf et al., 2022). However, simulated  
621 transpiration ratios at Berste, Vetschauer and Dobra were ~10% higher than the PML estimates,  
622 consistent with the limited fractionation shown in the streamwater isotopes. The temporally

623 coarse sampling potentially underestimated the seasonally aggregated fractionation, but the  
624 general seasonal variations were captured in the data. In addition, uncertainties in this remote  
625 sensing product cannot be discounted. In contrast at Wudritz, the simulated ratios were more  
626 consistent with the PML values. The mismatch in transpiration ratios may have resulted by  
627 underestimated evaporation from calibration with seasonally sampled isotopes, though this  
628 may be counterbalanced by unaccounted surface water evaporation from lakes in the former  
629 mining area. While evaporation from small open water bodies has negligible impacts on overall  
630 the catchment water balance, it can play an important role in isotopic enrichment (Birkel et al.,  
631 2011). For instance: in the Wudritz (7.7% surface water area), isotopic concentrations in  
632 simulations were likely underestimated due to unmodeled surface water evaporation. The non-  
633 linear relationship between evaporation rate and isotopic enrichment, as described by the Craig-  
634 Gordon model (Craig and Gordon, 1965), explains this dynamic: early-stage evaporation  
635 induces stronger isotopic enrichment, approaching a threshold under constant environmental  
636 conditions (e.g., humidity, temperature). Thus, even relatively minor surface water evaporation  
637 can bias isotopic signatures which then impacts ET partitioning simulations.

638

639 Further, the small weight of isotopes in a scalar function combining multiple objectives meant  
640 that it was possible to help disentangle ET processes (Wu et al., 2023). This was also illustrated  
641 by the minor adaptations along the Pareto front at Vetschauer and Dobra. The normally  
642 contrasting transpiration ratios between different land uses (Schlesinger and Jasechko, 2014)  
643 were consistent with our simulations, and divergent LAIs in each land use explains these  
644 differences (Cao et al., 2022), although the PML estimation presented similar transpiration  
645 ratios among each land use. However, the transpiration ratios could be underestimated in  
646 specific land uses due to unparameterized irrigation effects (Paul-Limoges et al., 2022), and  
647 the local water use efficiency needs to be further evaluated to improve future modelling.

648

649 Despite uncertainties introduced by relatively coarse sampling, isotopes were still valuable in  
650 water partitioning (i.e., ET and runoff) in such heavily managed catchments, which has been  
651 shown to be an advantage compared to other potential calibration targets (e.g., ET, soil  
652 moisture; Wu et al., 2023). The preliminary assessment of ET partitioning through isotope-  
653 aided modelling provides evidence for assessing the water-use efficiency of different land uses,  
654 especially croplands. Isotope data at finer temporal resolution would likely help better constrain  
655 ET partitioning in such heavily modified catchments, as they do in less disturbed environments  
656 (Tunaley et al., 2017; Soulsby et al., 2015). In addition, precipitation isotopes were from a  
657 global data product (Bowen et al., 2005). The use of interannually averaged monthly values  
658 likely failed to capture short-term climate variability or anthropogenic influences (e.g., fossil  
659 fuel-derived vapor), and may introduce uncertainties in water source apportionment (Xia et al.,  
660 2024; Yang and Yoshimura, 2024), though given the groundwater dominance and older (>5  
661 years) ages of runoff (Smith et al., 2021), the effects are likely to be small. Again, high  
662 resolution local data would be advantageous to improve such estimates.

663

664

#### 665 **4.3 Insights from contrasting discharge-isotope trade-offs among the four catchments**

666 Trade-offs in the calibrations between streamflow and isotopes are a well-known feature of  
667 TAM (Holmes et al., 2020), though their severity varies across applications. The extent of these  
668 compromises depends on the model's structural flexibility to assimilate additional constraints  
669 (Holmes et al., 2020) and the weightings given (Wu et al., 2025). Whilst some applications  
670 based on spatially-distributed models presented relatively minor conflicts in the information  
671 content of different calibration targets (Kuppel et al., 2018), significant degradation in  
672 streamflow performance has been found in lumped models after incorporating isotopes in

673 calibration (Fenicia et al., 2008). In our study, the lack of explicit representation of some  
674 anthropogenic drivers (e.g., water abstraction, irrigation etc.) in the model emerged as a likely  
675 contributor to trade-offs. Without explicit parameterization for these factors, the model often  
676 failed to fully capture flow dynamics in the catchments.

677

678 There was evidence for such systematic biases. For example, discharge-dominated solutions  
679 in isotope-aided calibrations produced a soil water-driven runoff regime that generally  
680 underestimated baseflow. The STARR model derived a fast draining process in the shallow  
681 subsurface layer (soil storage in the STARR) to simulate flattened isotope variations. Water in  
682 the shallow subsurface flows to the outlet through direct discharge (faster draining lead to lower  
683 evaporation and lower fractionation) and to the groundwater through seepage (high  
684 groundwater storage flattening isotope variations). In terms of discharge, high groundwater  
685 storage would typically result in flattened seasonal variations and elevated baseflows, whereas  
686 rapid draining of soil storage to discharge resulted in quick runoff response to rainfall, as  
687 illustrated by the isotope-dominated solutions (Figure S4). However, in the studied region, only  
688 the Vetschauer catchment showed both a rapid response to rainfall and high baseflow, and  
689 therefore showed relatively minor trade-offs between isotopes and discharge in the modelling.  
690 In contrast at the Berste catchment, discharge exhibited low base flow and pronounced seasonal  
691 variations but lacked a rapid response to rainfall events, which was inconsistent with the  
692 hydrological processes inferred by isotope observations. As all four catchments are located  
693 within the same region, with broadly similar soil cover, it might be expected that the soil  
694 hydrological response would be similar among the four catchments. However, the Berste, with  
695 the largest area, had the lowest base flows and slower responses to rainfall events compared.  
696 Considering the Berste catchment has the most extensive cropland coverage and high (but  
697 unknown) irrigation withdrawals, these trade-offs could be potentially explained by

698 management measures. Moreover, the higher groundwater contribution at Berste and Wudritz,  
699 compared to Vetschauer and Dobra, might be explained irrigation water withdrawals. Extraction  
700 of groundwater to the surface could dampen isotope variations in stream water, although much  
701 of the water volumes are expected to evaporate during summer period. Therefore, the un-  
702 represented water extraction process likely introduces more conflicts between discharge and  
703 isotope observations.

704

705 These trade-offs would likely be mitigated by more process-based conceptualizations of  
706 anthropogenic impacts (e.g. irrigation), though at the expense of greater parameterization and  
707 higher uncertainty. The STARR model's simplified routing structure, where runoff from  
708 contrasting sources follows identical pathways to the outlet, diverges from more physics-based  
709 frameworks that better spatially differentiate the timing of contributions of overland flow,  
710 unsaturated zone flow, and groundwater flow. This conceptual routing can capture flow  
711 dynamics in the stream, but likely mis-represent flow partitioning and creating conflicts in  
712 multi-criteria calibrations (McDonnell and Beven 2014). An additional point is that STARR  
713 didn't include any consideration of channel leakage and parameterization of the hyporheic flow  
714 could potentially and partly explain the flattened isotope variation and over-estimated baseflow  
715 simulations. This is a particular problem in former mining areas where recovery after historic  
716 groundwater is incomplete or has altered local groundwater surface water interactions  
717 increasing the possibility of streams having "losing" reaches with vertical leakage into  
718 groundwater (Pohle et al., 2025).

719

720 Further, STARR calculates ET solely based on water availability and partitions PET into PE  
721 and PT using a simplified single calibrated parameter. In contrast, more physically-based  
722 models, such as EcH2O-iso (Kuppell et al., 2018), explicitly simulate runoff generation

723 processes and compute ET through coupled energy and water balance equations, and thus likely  
724 better integrate isotopic information. While such enhancements improve a model's ability to  
725 simultaneously reconcile flow velocity and celerity, they also introduce greater parameter  
726 uncertainty (Herrera et al., 2022), and a trade-off between benefits of increased model  
727 complexity and increased simulation uncertainty will result (Schilling et al., 2019). Simple  
728 explicit modeling of water extraction for irrigation (e.g., channel-to-cropland transfers) could  
729 alleviate trade-offs observed in this study. However, sparse records of withdrawal volumes,  
730 associated irrigation patterns and potential unauthorized practices, as well as political  
731 sensitivities in data sharing may limit practical modelling.

732

733 Despite having relatively limited streamwater isotope samples compared to some other studies,  
734 their availability was invaluable for this intercomparison and revealed some significant  
735 difference between catchment function (Figure 3). Since the evaluation of trade-offs between  
736 discharge and isotopes primarily relied on the seasonal patterns of isotopes, the three years of  
737 seasonally sampled isotopes used for calibration and the monthly rainfall isotope inputs provide  
738 a sufficient basis for evaluation for the trade-offs. In addition, the potential anthropogenic  
739 impacts noted above were identified through the comparisons among the four catchments in  
740 the same region, further supporting the value of the analysis. This evaluation of trade-offs  
741 between discharge and isotopes helped identify potential processes not adequately captured  
742 through discharge alone in such a heavily managed catchment.

743

## 744 **5 Conclusions**

745 Stable water isotopes are valuable tracers for identifying water sources, offering the potential  
746 to constrain ecohydrological models. While model calibration in natural catchments typically

747 exhibits slight trade-offs between isotopic signatures and conventional hydrological variables  
748 (usually discharge), this study advances a novel perspective on the benefits and challenges of  
749 integrating isotopes in catchments heavily impacted by human activities. Using the conceptual-  
750 based, fully-distributed TAM in the STARR model, we calibrated both isotopes and streamflow  
751 without explicitly parameterizing anthropogenic disturbances to investigate three critical issues:  
752 (1) the potential of using discharge alone in calibration to mislead process interrelations from  
753 simulations under anthropogenic stress, and (2) the adaptability and value of seasonally  
754 sampled isotopes in such contexts, and (3) the likely impacts of human interventions on model  
755 performance. We studied four sub-catchments of the Middle Spree (Berste, Wudritz,  
756 Vetschauer, and Dobra), subjected to contrasting anthropogenic pressures (long-term mining  
757 impacts, seasonal water withdrawals), and derived Pareto-optimal solutions to help disentangle  
758 the additional insights provided by isotope-aided calibration compared with streamflow alone.

759 The results demonstrate that discharge-only based calibrations could mis-represent runoff  
760 partitioning processes, especially in catchments with water withdrawals for irrigation, while  
761 isotopes helped identify implausible simulations by being more informative on process  
762 representation. For example, higher groundwater contributions were identified through  
763 isotope-aided calibrations. Isotopes also helped to disentangle ET partitioning, although  
764 seasonally sampled isotopes could underestimate seasonally aggregated fractionations, and the  
765 absence of explicitly parameterizing the hydrology of small mining lakes could potentially  
766 mislead the results. Strong trade-offs between isotopes and streamflow in calibrations arise in  
767 such anthropogenically-impacted catchments, where unquantified epistemic errors in  
768 streamflow observations caused by human activities can compromise model reliability.

769 This study highlights how unaccounted anthropogenic activities can alter model interpretations  
770 and underscores the complementary role of isotopes and TAMs in refining simulations under  
771 complex human-environment interactions, although only seasonally sampled isotopes were

772 employed. While distinct trade-offs between streamflow and isotopes were observed in the  
773 study catchments, these simulations still offer informative insights into ecohydrological  
774 dynamics and partitioning in heavily impacted catchments, even when quantitative process  
775 evaluation remains challenging. In catchments subject to intensive anthropogenic interventions  
776 (e.g., altered water distribution via irrigation or withdrawals), the severity of streamflow-  
777 isotope conflicts and compromises in TAM may serve as an indirect diagnostic of human  
778 impacts on water partitioning. Representing anthropogenic effects in ecohydrological models  
779 is inherently difficult, particularly when historical data on water use or management practices  
780 are sparse. However, we demonstrated here that TAMs have valuable potential in such  
781 applications and encourage greater isotope sampling in anthropogenically influenced  
782 catchments.

783

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796

#### 797 **Code and data availability**

798 The model codes and the data are available upon request.

799

800 **Competing interests**

801 The authors declare that they have no conflict of interest.

802

803 **Author contributions**

804 HZ: Conceptualization, Data curation, model set-up, calibration and validation, analysis and plotting,

805 Methodology, Writing – original draft preparation. DT: Investigation, Funding acquisition, Data curation,

806 Methodology, Formal analysis, Writing – review & editing. CB: Methodology, Formal analysis, Writing – review

807 & editing. SW: Methodology, Formal analysis, Writing – review & editing. TS: Methodology, Writing – review

808 & editing. CS: Conceptualization, Methodology, Formal analysis, Writing – review & editing.

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