



Supplement of

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

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1 **Supplementary materials:**

2 **S1: Hydrological components in the original STARR model**

3 The main reservoir structures in the model consist of four parts: canopy interception, soil
4 storage, stream water, and groundwater storage, while the dynamics and interactions of these
5 storages are determined by the hydrological processes (e.g., Rainfall, Evapotranspiration (ET),
6 Infiltration, Seepage, Capillary flux and etc.) (Fig. 1). All equations are summarised in Table
7 S1. Interception is replenished through a certain fraction of the rain hitting the canopy and the
8 flux processes (throughfall) are simulated following Rutter et al. (1972), while the maximum
9 interception storage capacity depends on the leaf area index (LAI; Von Hoyningen-Huene,
10 1981). Potential evapotranspiration (PET) is calculated following the method in the HYPE
11 (Hydrological Predictions for the Environment) model (Lindström et al., 2010), while the
12 actual evapotranspiration is subject to water availability in interception and soil storage.
13 Instantaneous surface runoff is produced when soil storage exceeds the maximum storage
14 capacity, while the discharge from soil and groundwater to the stream is linearly related to soil
15 and groundwater storage, respectively. These three runoff components constitute streamflow
16 and flow routing of all runoff components is determined by setting a fixed celerity. The soil
17 and groundwater storages are interconnected through seepage (from soil to groundwater) and
18 capillary flux (from groundwater to soil), both of which depend on the soil storage value in
19 relation to maximum soil storage capacity. Lateral groundwater flow processes are linearly
20 determined by the slope of the landscape.

21 Isotope signatures of each water component are calculated through mass balance equations,
22 assuming the mixing is complete and instantaneous. Isotope fractionation is only considered in
23 the interception storage and conceptualized as an empirical relationship on the basis of a simple
24 linear regression of deuterium signatures in gross rain. The ratio of the transpiration in ET is
25 determined by $(\delta_A - \delta_E) / (\delta_S - \delta_E)$ assuming that transpiration is a non-fractionation process

26 (Chakraborty et al., 2018), where δ_A , δ_E , δ_S are the isotopic compositions of ambient
27 atmospheric vapour, evaporation and soil water, respectively (Correa et al., 2020).

Table S1. The modified STARR model components and equations.

Process	Equations	Variables
Interception storage (Stevenson et al., 2023)		
Interception per timestep	$INV = (\alpha \times LAI) \times \left(1 - \frac{1}{1 + \frac{SCF \times P}{\alpha \times LAI}}\right)$	α : Empirical parameter LAI : Leaf area index SCF : Surface Cover Fraction P : Rainfall
Surface Cover Fraction	$SCF = 1 - e^{rE \times LAI}$	rE : Radiation extinction
Maximum interception capacity	$C_{sat} = 0.2001 + LAI \times 0.3001$	C_{sat} : canopy saturation volume
Evaporation from interception	$\begin{aligned} \text{If } INT < E_p: E_i &= INT \\ \text{Else: } E_i &= E_p \end{aligned}$	INT : interception storage
Drainage (Rutter et al., 1972)	$\begin{aligned} \text{If } INT > C_{sat}: \\ D &= D_s \times e^{b \times (INT - C_{sat})} \\ \text{Else: } D &= 0 \end{aligned}$	INT : Interception storage D : Drainage volume D_s : Empirical parameter b : Empirical parameter
Transpiration (Stevenson et al., 2023)		
Potential transpiration Potential evaporation	$\begin{aligned} T_p &= PET \times SCF \\ E_p &= PET - T_p \end{aligned}$	
Soil storage		
Instantaneous surface runoff	$Q_s = \max(STO - FC, 0)$	STO : Soil water storage FC : Soil water storage capacity
Evaporation from soil	$\begin{aligned} \text{If } STO < LP \times FC: E_s &= \frac{E_p - E_i}{LP \times FC} \\ \text{Else: } E_s &= E_p - E_i \end{aligned}$	LP : Fraction of soil water capacity above which $E_s = E_p$
Transpiration from soil	$T_s = T_p \times \frac{STO}{FC}$	
Seepage	$Seepage = \frac{STO}{FC^\beta}$	β : Empirical parameter
Soil discharge	$Q_{STO} = STO \times k_s$	k_s : Empirical parameter
Groundwater storage		
Capillary flux	$CapFlux = C_{flux} \times \frac{FC - STO}{FC}$	C_{flux} : maximum capillary rise
Transpiration from groundwater	$T_g = (T_p - T_s) \times \frac{STO}{GW_{max}}$	GW_{max} : maximum groundwater storage
Groundwater discharge	$Q_{GW} = GW \times k_g$	k_g : Empirical parameter GW : Groundwater storage

Lateral flow	$Q_{lf} = k_{sat} \times slope \left(\frac{DEM}{1000} + GW \right)$	k_{sat} : horizontal saturated conductivity $slope$: slope gradient
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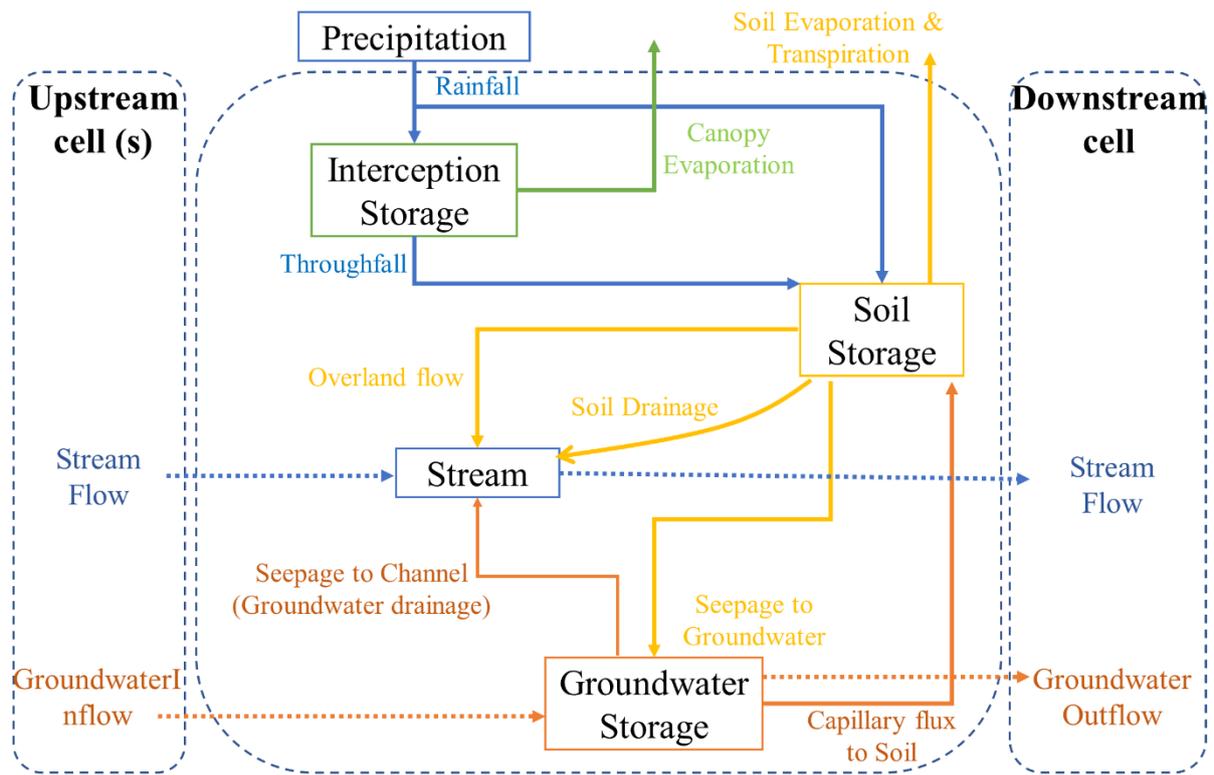
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Table S2. Initial ranges of the STARR model parameters.

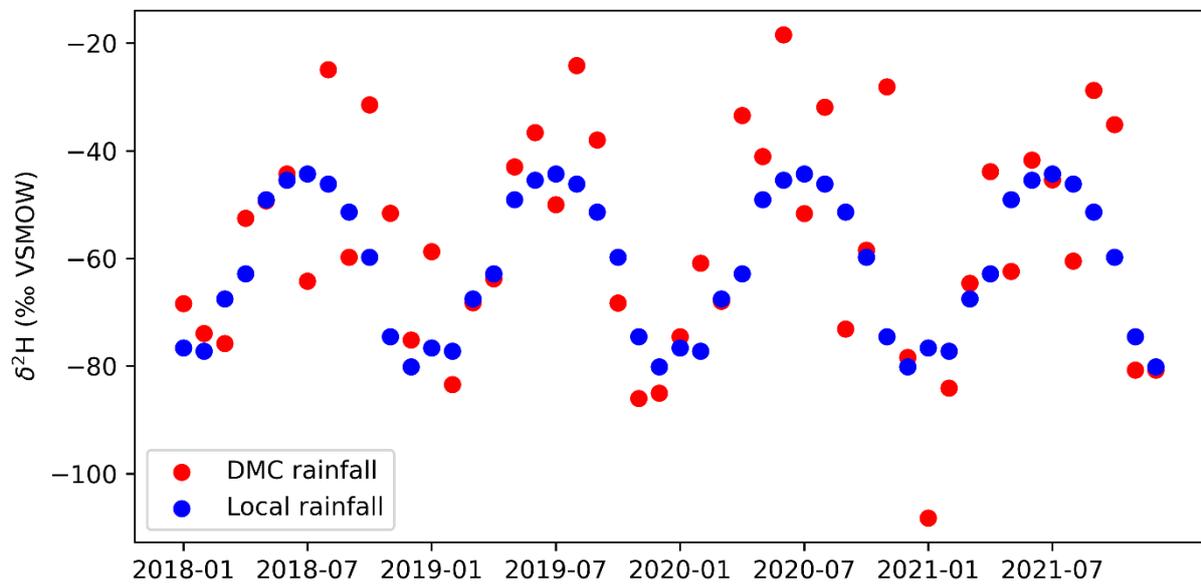
Parameter	Unit	Description	Initial range
Interception storage			
α	[cm/day]	Interception threshold parameter	0.5 - 3.5
rE	[-]	Radiation extinction by the canopy	0.2 - 0.8
D_s	[mm/day]	Drainage from canopy when the storage is full	0.1 - 1.2
b	[-]	Exponent in Rutter interception module	0.1 - 1.2
Soil Storage			
FC	[mm]	Water holding capacity	100 - 1000
LP	[-]	Fraction of soil saturation above which evaporation happens unlimited	0.05 - 0.5
BetaSeepage	[-]	Non-linear exponent for soil store runoff generation	0.01 - 5.5
k_s	[1/day]	Recession coefficient discharge from soil store	0.000001 - 0.5
Groundwater storage			
k_g	[1/day]	Recession coefficient for discharge from groundwater store	0.0008 - 0.1
k_{sat}	[mm/day]	Recession coefficient for discharge from groundwater store	0.0008 - 200.0
C_{flux}	[mm/day]	Capillary rise from groundwater module to soil store	0.05 - 30.0
GW_{max}	[mm]	Maximum groundwater storage	1 - 2000
Routing process			
n	[-]	Manning coefficient	Water, Channels: 0.025 Forest: 0.2 Pasture: 0.259 Shrub, Croplands: 0.259 Urban: 0.013

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33 Figure S1. Model structure and key components in the modified STARR model

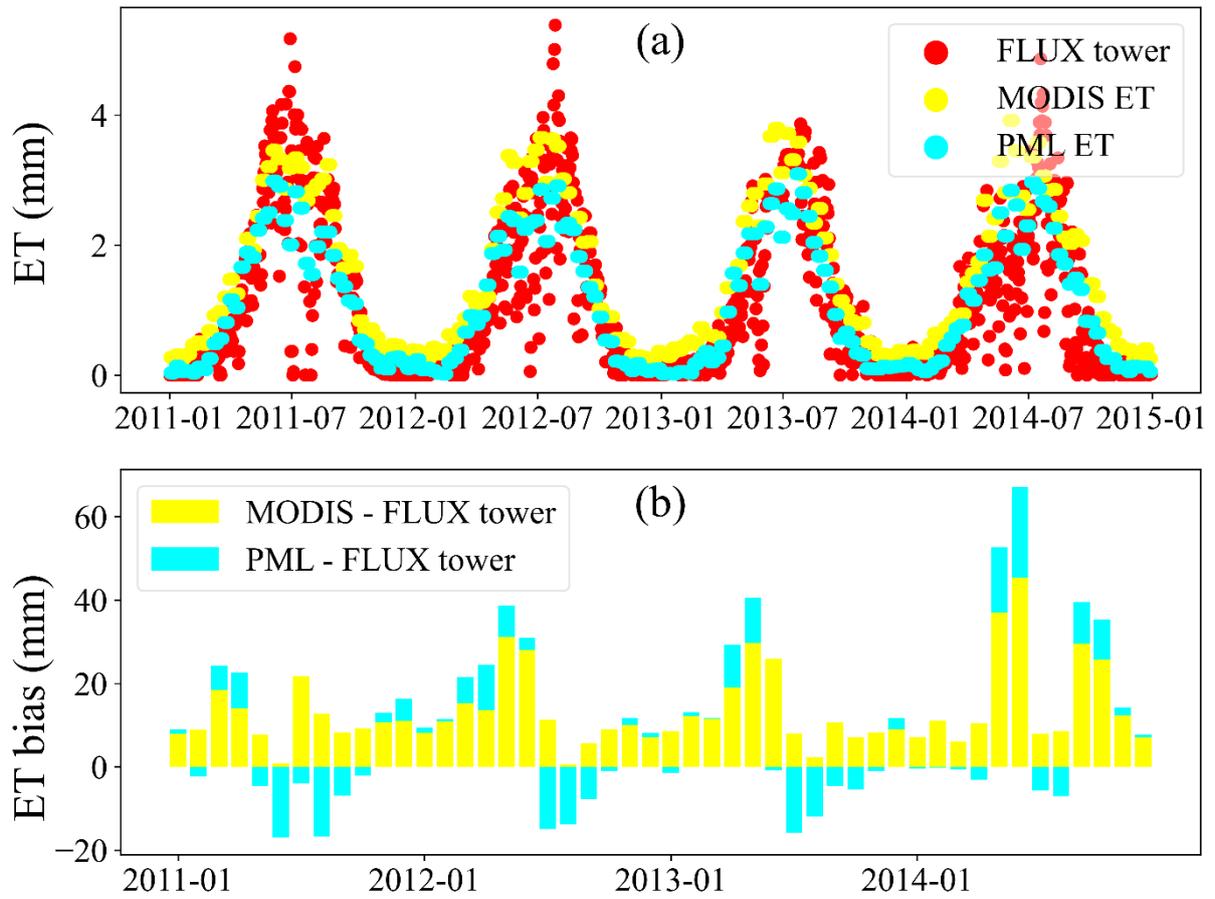


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35 Figure S2. The comparison of rainfall isotopes between the product used in the present study
 36 and a station downstream of the studied region.

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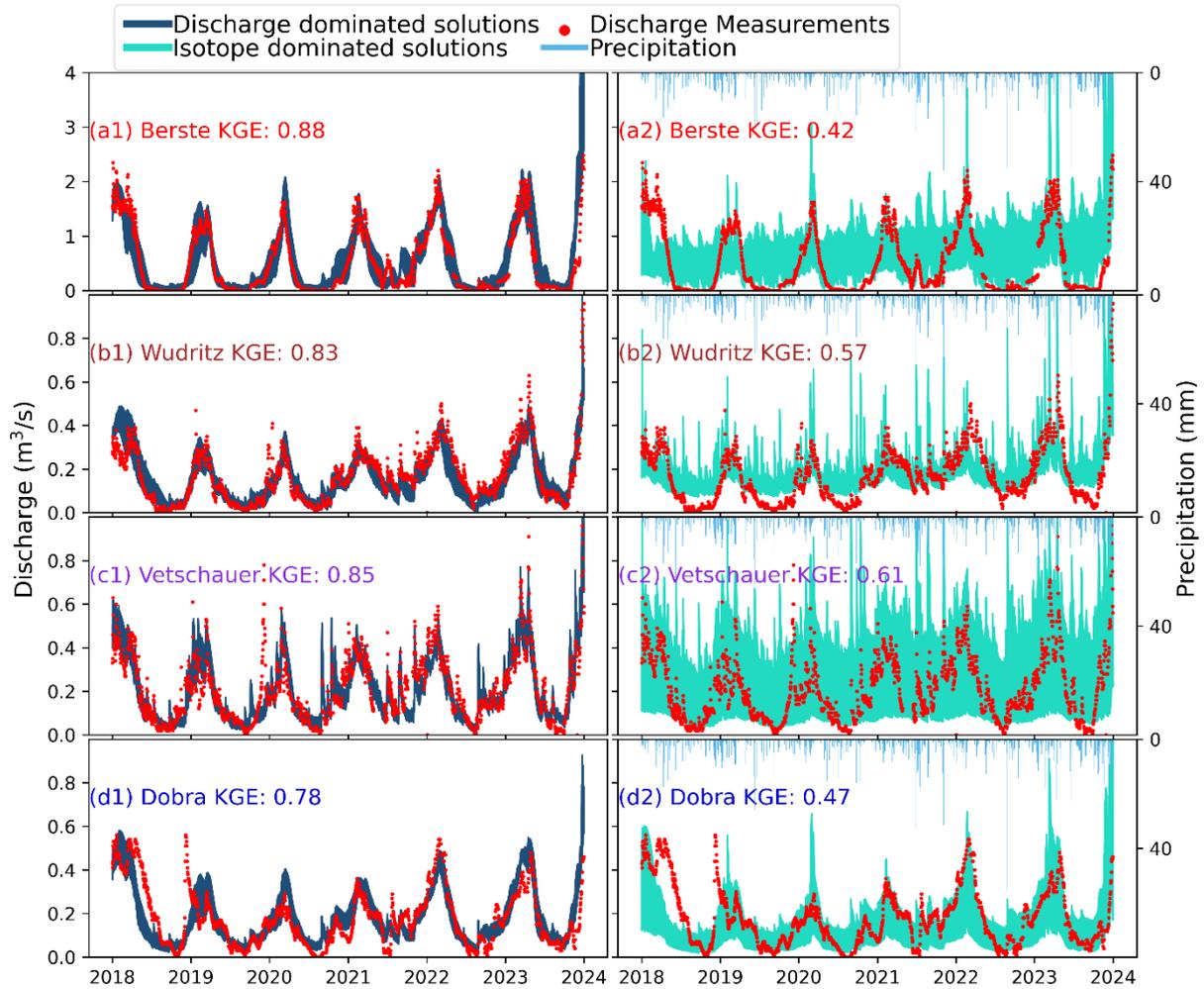
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41 Figure S3. Comparison of ET between a Flux tower (51.8922 N, 14.0337 E), MODIS and PML
 42 ET in the Spreewald. (a) Daily ET from Flux tower and 8-day ET from MODIS and PML; (b)
 43 Biased ET values between MODIS or PML and the Flux tower.

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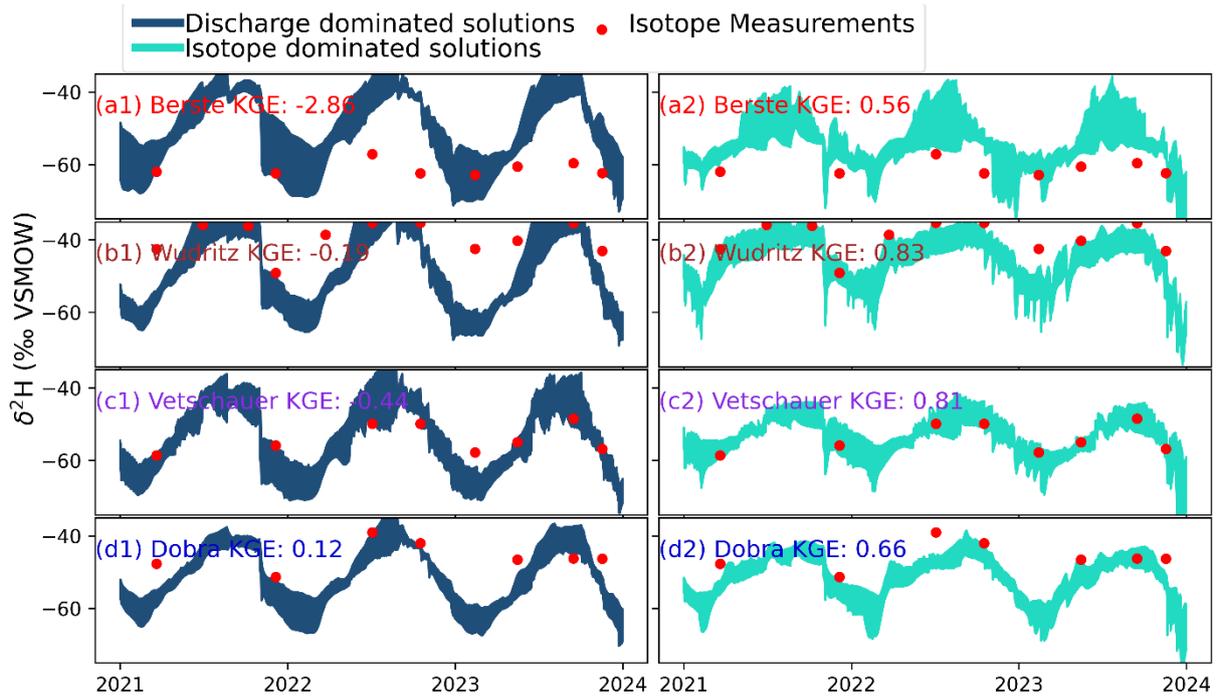


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46 Figure S4. Discharge simulations at the outlet of each catchment based on discharge or isotope
 47 dominated solutions in the corresponding calibration schemes. (a) Berste; (b) Wudritz; (c)
 48 Vetschauer; (d) Dobra. Suffix “1” (a1, b1, c1, d1) and “2” (a2, b2, c2, d2) in the subplot titles
 49 represent the discharge-dominated or isotope-dominated solutions, respectively.

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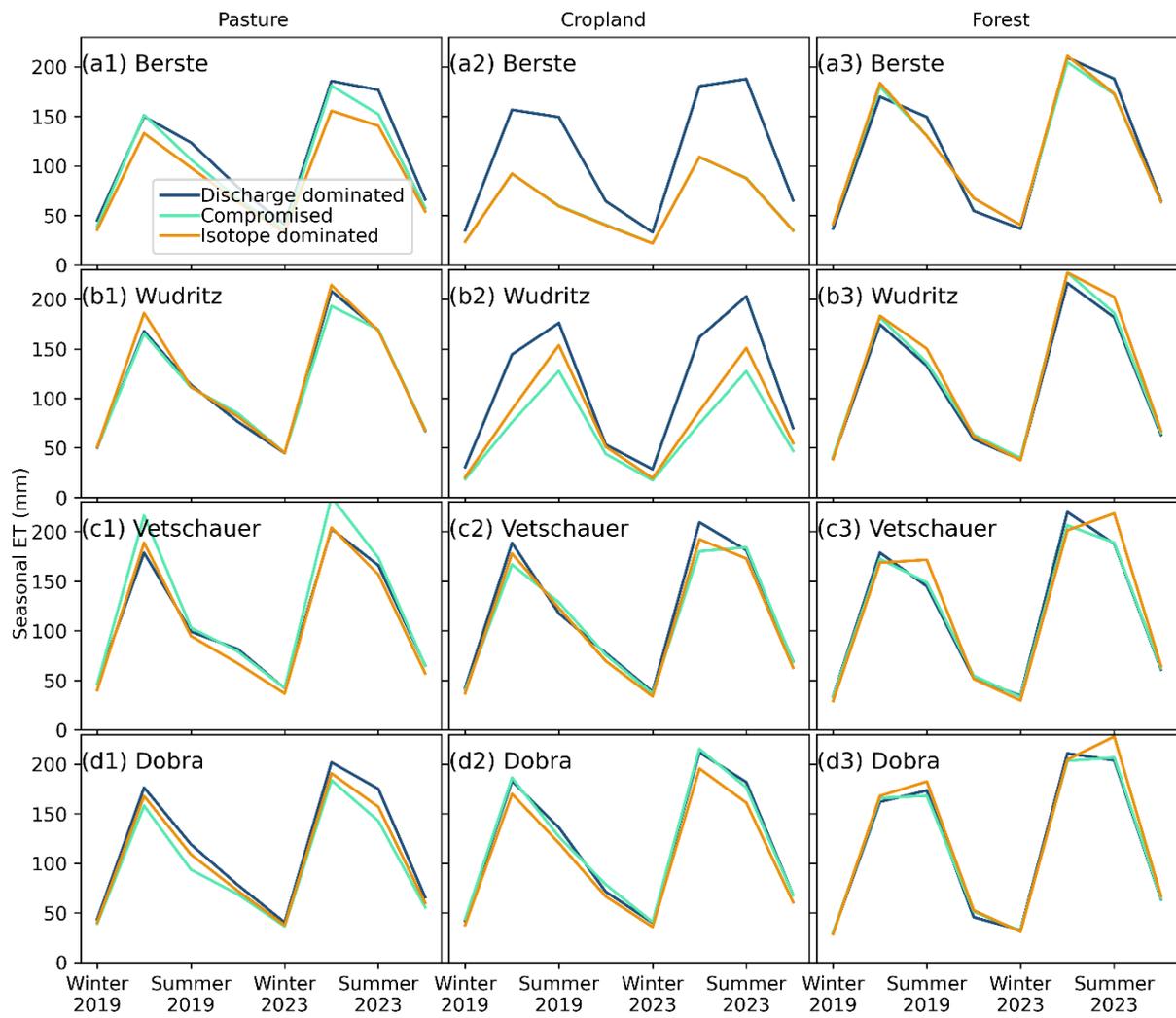
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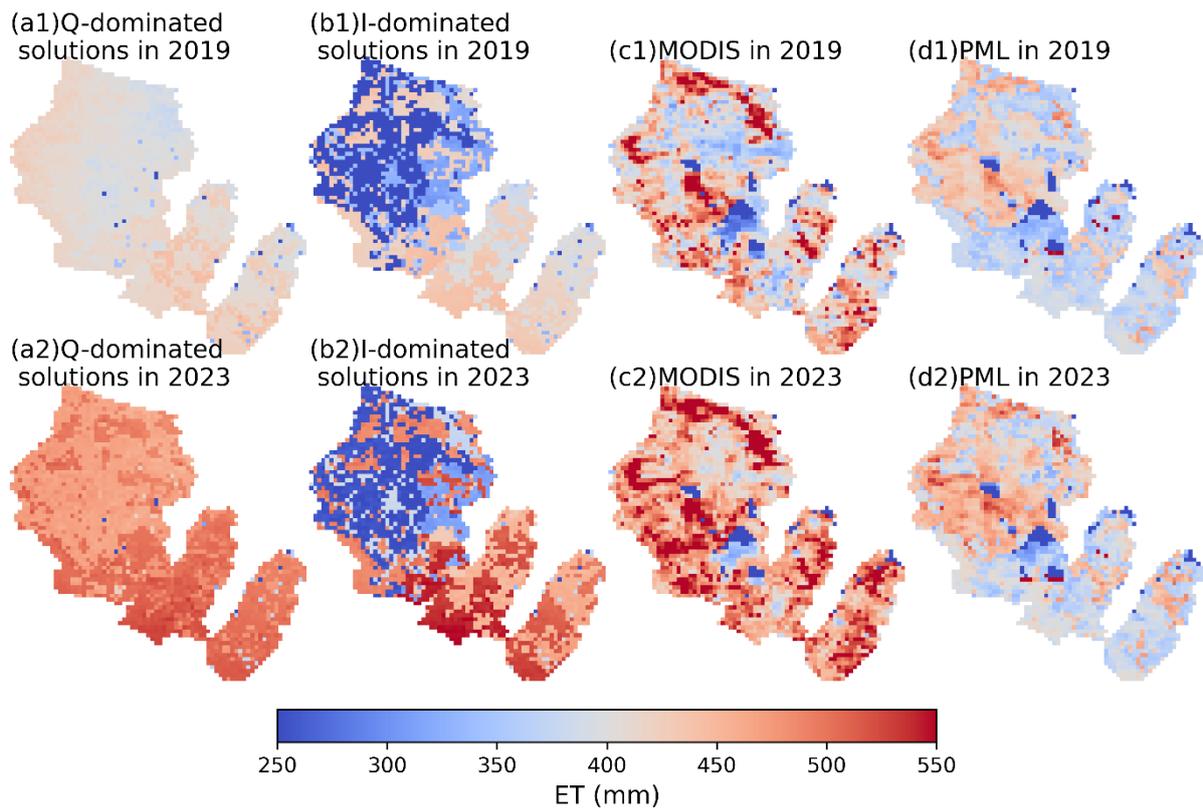
53 Figure S5. Stream water isotope simulations at the outlet of each catchment based on discharge
 54 or isotope dominated solutions in the corresponding calibration schemes. (a) Berste; (b)
 55 Wudritz; (c) Vetschauer; (d) Dobra. Suffix “1” (a1, b1, c1, d1) and “2” (a2, b2, c2, d2) in the
 56 subplot titles represent the discharge-dominated or isotope-dominated solutions, respectively.

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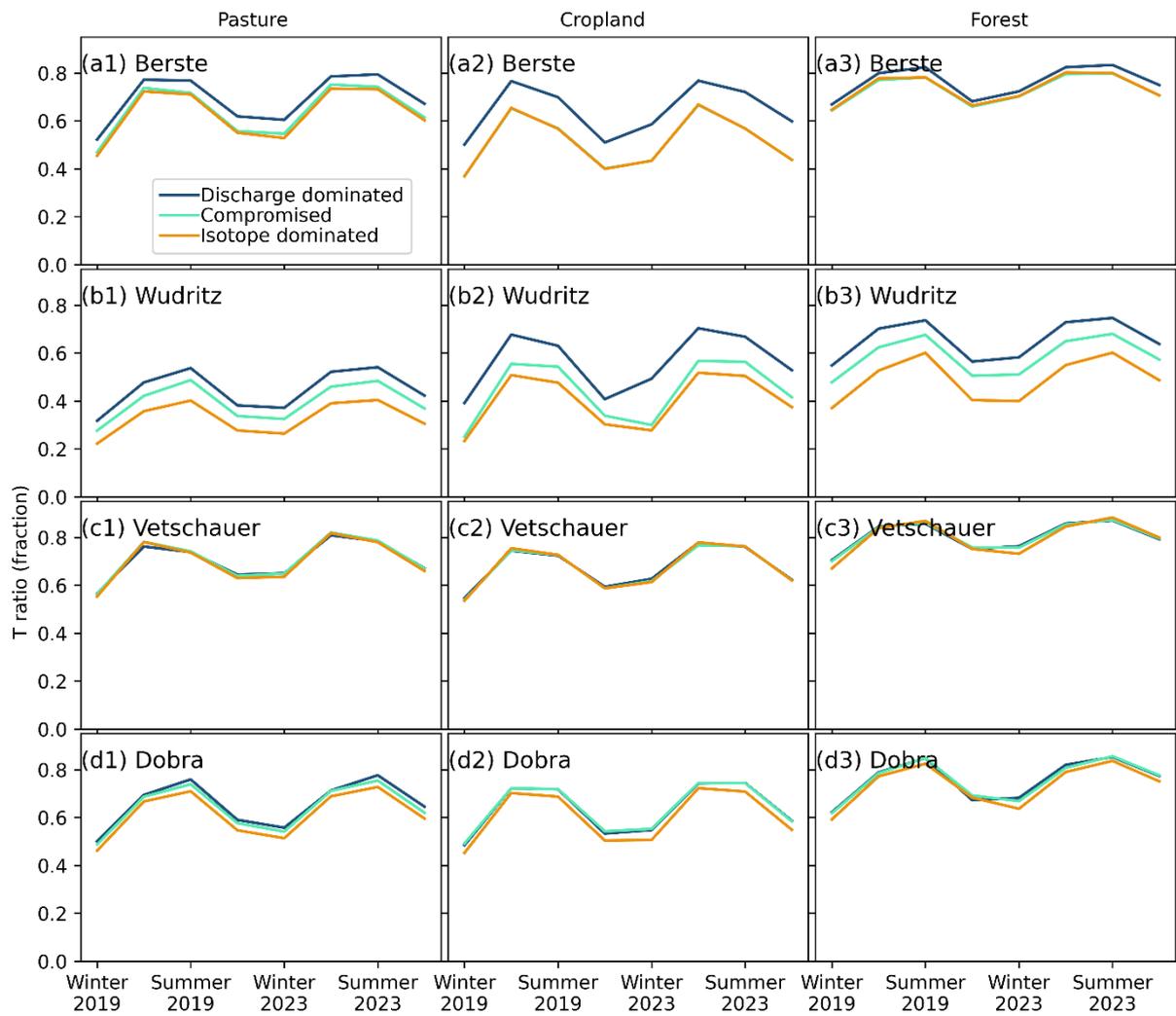
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59 Figure S6. Seasonal ET in the three land uses for each catchment during 2019 and 2023 (winter,
 60 spring, summer, fall of 2019 and 2023 along X-axis). The results were calculated from the
 61 discharge dominated, balanced and isotope dominated solutions in schemes 2-5.



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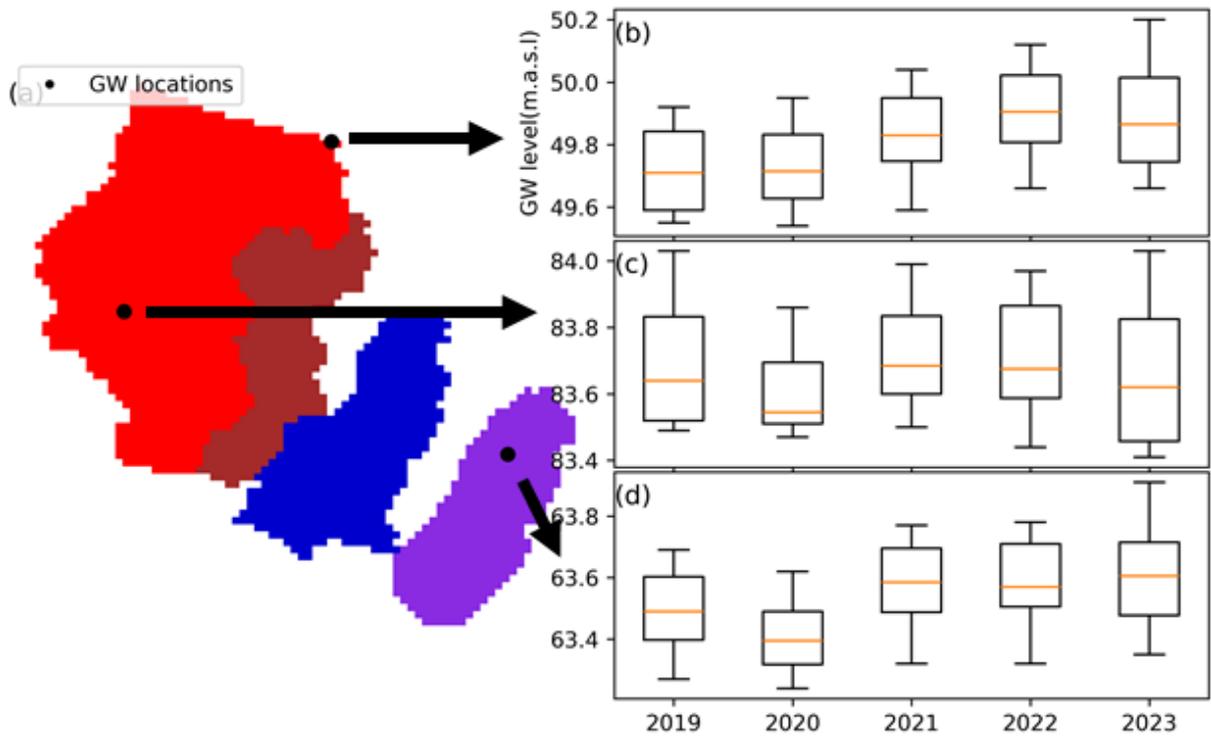
63 Figure S7. Spatial distribution of ET in the four catchments. (a) Discharge(Q)-dominated
 64 solutions in schemes 2-5; (b) Isotope(I)-dominated solutions in schemes 2-5; (c) MODIS ET;
 65 (d) PML ET. Suffix “1” (a1, b1, c1, d1) and “2” (a2, b2, c2, d2) in the subplot titles mean dry
 66 year of 2019 and wet year of 2023, respectively.



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68 Figure S8. Transpiration ratio of each season in the three land uses for each catchment during
 69 2019 and 2023 (winter, spring, summer, fall of 2019 and 2023 along X-axis). The results were
 70 calculated from the discharge dominated, balanced and isotope dominated solutions in schemes
 71 2-5.

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74 Figure S9. Measured groundwater level in the studied region. (a) GW locations, (b-d) annually
75 varied GW level (hydrological year). Each boxplot in (b-d) covers all recorded levels in the
76 corresponding hydrological year.

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