Title: The role of rock fractures on tree water use of water stored in bedrock: Mixing and residence times

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Reviewer 1:

Comments on egusphere-2025-3937

This study employs a combination of stable isotope tracing, the MixSIAR Bayesian mixing model, and hydrometric observations to quantitatively analyze the spatiotemporal variations in tree water sources within karst regions, and to explore the role of rock fractures in tree utilization of bedrock-stored water. The research topic is of considerable scientific significance and shows a reasonable degree of originality, providing valuable insights into plant water-use strategies and ecohydrological coupling mechanisms under complex lithological conditions. Overall, the study presents a clear research framework and is supported by adequate data; however, improvements are needed in the description of experimental details, the clarity of figure presentation, and the logical interpretation of results. I recommend a major revision before the manuscript can be considered for publication.

Response: We sincerely thank the reviewer for the careful and constructive evaluation of our manuscript. We appreciate the positive assessment of the scientific significance and originality of this work. We fully agree that improvements are needed in the description of experimental details, figure clarity, and interpretation of results. Below, we respond point-by-point to all comments and clearly indicate how each issue will be addressed in the revised manuscript.

1. L130-133: It is recommended to present the sampling information in a table, including details such as the number of samples and sampling frequency. In addition, the current description of different depths is rather vague.

Response: We thank the reviewer for this important suggestion. In the revised manuscript, detailed sampling information is now summarized in a series of tables. Specifically, Table A1 provides an overview of soil moisture monitoring and soil water sampling design, including site-specific sampling depths, sampling frequency, and sampling periods for bulk soil water and mobile soil water. Additional tables (Tables A2 and A3) summarize the corresponding sampling design for rock water and tree xylem water, respectively. The number of collected samples for each water compartment is reported in Tables B1–B4. In addition, the Methods section has been revised to replace the previous depth range description with explicit reference to predefined discrete sampling depths, thereby removing ambiguity in the description of soil depth.

Revised manuscript text: The method for collecting mobile soil water and bulk soil water samples at different depths involved two preparatory steps: (1) soil boreholes were manually drilled using a soil auger to predefined discrete depths at each study site.; (2) at selected depths, soil material was removed and ceramic tensiometer tips connected to suction lysimeters were installed for the collection of mobile soil water. The boreholes were then backfilled with the original soil to ensure proper contact and minimize disturbance. Bulk soil samples were collected at all predefined depths and bulk soil water was subsequently extracted from the collected soil samples using laboratory extraction methods. The site-specific sampling depths, sampling frequency, and sampling periods for bulk soil water and mobile soil water are summarized in Table A1.

Table A1. Summary of soil moisture monitoring and soil water sampling design across study sites.

Category		Soil moisture monitoring	Bulk soil water sampled	Mobile soil water sampled
Dates		Sep 2022–Jun 2025	Apr 2024–Mar 2025	Sep 2022–Nov 2024
Frequency		30 min	Dry season: once per month; rainy season: 1–2 times per month	Dry season: once per month; rainy season: 1–4 times per month
Depths at defferent sites (cm)	A	5, 20, 50, 100, 150	5, 20, 50, 70, 100, 150	50, 100
	B	5, 20, 50, 100, 180	5, 20, 50, 70, 100, 180	20, 50, 100, 180
	C & D	5, 20, 40, 50	5, 20, 30, 40, 50	20, 40, 50
	E	5, 30, 50, 100	5, 30, 50, 70, 100	30, 100

Table B1. Statistics of MRT and MTT (day) for mobile and bulk water in different soil layers.

Site	Depth (cm)	K_h (cm·h^{-1})	Average moisture content	Mobile soil water					Bulk soil water				
				MRT	MTT	Number of samples	R^2	Standard error	MRT	MTT	Number of samples	R^2	Standard error
A	5	3.83	0.153	-	-	-	-	-	36	6	16	0.75	19.08
	20	3.33	0.223	-	-	-	-	-	65	16	16	0.89	11.20
	50	2.33	0.264	72	15	68	0.56	18.15	139	26	16	0.67	8.48
	70	2.18	-	-	-	-	-	-	155	28	16	0.54	8.46
	100	1.96	0.133	74	31	36	0.83	11.77	138	32	16	0.64	9.96
B	5	0.58	0.212	-	-	-	-	-	49	10	16	0.80	11.74
	20	0.44	0.245	63	23	23	0.61	9.35	177	31	16	0.55	9.01
	50	0.16	0.241	459	34	38	0.52	2.09	471	73	16	0.50	9.00
	70	0.17	-	-	-	-	-	-	638	82	16	0.54	6.82
	100	0.18	0.125	244	43	40	0.54	5.34	685	47	16	0.50	5.41
	180	0.10	0.182	77	24	25	0.64	10.59	708	63	16	0.53	4.84
C&D	5	4.96	0.191	-	-	-	-	-	40	6	16	0.78	17.07
	20	1.04	0.261	85	25	51	0.68	12.28	60	12	16	0.81	11.02
	30	1.04	-	-	-	-	-	-	66	9	16	0.83	13.13
	40	1.04	0.209	85	33	45	0.74	11.04	63	12	16	0.87	10.71
	50	1.04	0.209	63	20	49	0.83	11.77	95	17	16	0.93	7.18
E	5	1.42	0.309	-	-	-	-	-	47	8	16	0.83	13.63
	30	0.75	0.227	122	38	33	0.57	9.77	108	19	16	0.68	12.30
	50	0.75	0.298	-	-	-	-	-	131	27	16	0.85	8.95
	70	0.83	-	-	-	-	-	-	118	24	16	0.88	7.79
	100	0.96	0.204	144	32	48	0.50	9.84	121	17	16	0.74	9.41
Mean	51	1.39	0.217	135	29	41	0.64	10.18	196	27	16	0.72	10.25

Table A2. Summary of rock moisture monitoring and rock water sampling design across study sites.

Category		Rock moisture monitoring	Rock water sampled
Dates		Sep 2022–Jun 2025	Sep 2022–Mar 2025
Frequency		30 min	Dry season: once per month; rainy season: 1–4 times per month
Depths at defferent sites (cm)	A	20, 62, 105, 147, 220, 270	62, 147, 270, 600
	B	45, 50, 60, 80, 100, 150, 180	45, 50, 60, 80, 100, 150, 180
	C & D	20, 40, 79, 94, 165, 176, 200, 244, 306	79, 94, 165, 176, 200, 244, 306
	E	170, 207	170, 207, 248
Fracture apertures at defferent sites (mm)	A	0.54, 0.8, 0.92, 1.89, 3.06, 6.45	1.89, 3.06, 5, 6.45
	B	0.47, 0.5, 0.55, 1.43, 10, 15, 21	0.47, 0.5, 0.55, 1.43, 10, 15, 21
	C & D	0.16, 0.2, 0.26, 2, 20, 30, 35, 38	0.16, 0.26, 2, 20, 30, 35, 38
	E	2.4, 2.6	1.84, 2.4, 2.6

Table B3. Statistics of MRT and MTT (day) for fractures of different apertures and depths.

Site	Aperture (mm)	Depth (cm)	Porosity (ε_p)	K_h ($cm{\cdot}h^{-1}$)	Average moisture content	MRT	MTT	Number of samples	R^2	Standard error
C&D	0.16	306	1	0.09	0.354	124	31	54	0.56	11.30
C&D	0.26	244	1	1.13	0.256	118	34	43	0.63	10.80
B	0.47	60	1	3.04	0.217	57	24	44	0.72	14.04
B	0.50	45	1	3.42	0.310	23	-2	30	0.70	17.44
B	0.55	50	1	3.71	0.217	91	25	59	0.50	17.77
B	1.43	80	0.98	17	0.260	76	22	34	0.64	14.03
E	1.8	248	0.75	13	-	73	20	34	0.72	14.84
A	1.89	270	0.98	673	0.217	108	30	61	0.61	14.62

Site	Aperture (mm)	Depth (cm)	Porosity (ε_p)	K_h (cm·h^{-1})	Average moisture content	MRT	MTT	Number of samples	R^2	Standard error
C&D	2	79	0.74	76	0.256	35	2	60	0.73	15.13
E	2.4	170	0.6	34	0.413	103	29	23	0.55	12.06
E	2.6	207	0.54	47	0.413	97	33	70	0.75	10.23
A	3.06	62	0.80	40	0.203	60	22	44	0.69	13.90
A	5	600	0.66	3496	-	182	29	47	0.50	6.21
A	6.45	147	0.55	6208	0.317	100	24	38	0.69	9.75
B	10	100	0.41	6	0.206	136	27	38	0.55	12.20
B	15	180	0.45	33	0.158	84	21	44	0.57	12.85
C&D	20	200	0.47	315	0.311	176	25	53	0.60	8.63
B	21	150	0.74	1042	0.188	198	38	25	0.55	12.20
C&D	30	165	0.49	87	0.311	303	20	25	0.54	6.90
C&D	35	176	0.74	2232	0.311	169	38	43	0.50	9.22
C&D	38	94	0.70	2746	0.256	200	24	50	0.61	6.23
Mean	9.41	173	0.74	813	0.272	120	25	44	0.61	11.92

Table A3. Summary of tree-based sampling design and root-zone characteristics across study sites.

Site	Tree number	Species	Characteristics of root zone			Characteristics of trees			
			Soil depth (cm)	Soil volume (m^3)	Fracture volume (m^3)	Height (m)	DBH (cm)	Canopy area (m^2)	Sapwood area (cm^2)
A	bp_1	*Broussonetia papyrifera* (L.) L'Hér. ex Vent.	200	1.68	1.30	7.00	29.60	62.83	499
	bp_2		200	0.67	0.52	7.00	12.80	25.04	82.60
	bp_3		200	1.26	0.98	7.00	22.00	47.12	219
B	ts_1	*Toona sinensis* (A.Juss.) M.Roem.	43	1.12	0.04	5.50	5.40	1.30	18.36
	ts_2		22	0.42	0.05	5.80	5.80	1.51	19.23

Site	Tree number	Species	Characteristics of root zone			Characteristics of trees			
			Soil depth (cm)	Soil volume (m^3)	Fracture volume (m^3)	Height (m)	DBH (cm)	Canopy area (m^2)	Sapwood area (cm^2)
C	ts$_5$	*Toona sinensis*	16	0.12	0.61	11.50	10.77	14.00	34.19
	ts$_6$	(A.Juss.) M.Roem.	60	6.88	2.19	12.35	36.00	50.46	593
	cc$_3$	*Cinnamomum camphora* (L.) J.Presl.	52	0.71	0.95	7.00	11.73	21.90	59.24
	yd$_1$	*Yulania denudate*	53	0.37	0.44	6.00	9.63	10.07	38.45
	yd$_2$	(Desr.) D.L.Fu	52	1.42	0.33	7.00	12.75	7.52	16.34
D	ts$_3$	*Toona sinensis*	24	0.22	1.01	10.50	10.00	10.40	31.27
	ts$_4$	(A.Juss.) M.Roem.	60	0.32	1.33	10.50	9.50	13.70	29.52
	cc$_1$	*Cinnamomum camphora*	24	0.22	1.65	10.00	13.40	17.01	96.54
	cc$_2$	(L.) J.Presl.	30	0.68	1.50	8.00	14.39	15.47	128
E	bp$_4$	*Broussonetia papyrifera*	100	2.40	0.38	6.70	16.00	28.04	116.50
	bp$_5$	(L.) L'Hér. ex Vent.	15	0.15	0.41	6.50	13.30	30.68	87.26
	kp$_1$	*Koelreuteria paniculate*	20	0.19	0.06	7.00	8.00	4.24	30.44
	kp$_2$	Laxm.	20	0.18	0.04	5.80	6.80	2.83	23.12

Table B4. Statistics of MRT and MTT (day) for different trees at typical sites in the study area.

Site	Tree number	From mobile soil water to tree		From bulk soil water to tree		From rock water to tree		Number of samples	R^2	Standard error
		MRT_1	MTT_1	MRT_2	MTT_2	MRT_3	MTT_3			
A	bp$_1$	53	-1	58	5	47	-4	45	0.55	13.40
	bp$_2$	59	5	64	10	53	1	45	0.52	14.70
	bp$_3$	39	-8	44	-3	31	-12	45	0.57	14.41
B	ts$_1$	14	0	38	-13	79	3	44	0.52	13.96
	ts$_2$	40	-7	94	-3	101	-3	44	0.60	10.72

Site	Tree number	From mobile soil water to tree		From bulk soil water to tree		From rock water to tree		Number of samples	R^2	Standard error
		MRT_1	MTT_1	MRT_2	MTT_2	MRT_3	MTT_3			
C&D	ts_3	18	-9	60	8	54	7	44	0.63	10.29
	ts_4	22	-10	48	6	51	7	44	0.68	9.07
	ts_5	8	-9	32	7	25	7	44	0.60	10.13
	ts_6	96	2	124	18	128	19	44	0.67	7.78
	cc_1	42	-4	79	13	73	12	44	0.72	11.13
	cc_2	43	-1	80	15	74	14	44	0.72	11.18
	cc_3	45	2	68	19	71	19	44	0.77	11.91
	yd_1	37	-15	60	1	63	2	44	0.54	9.83
	yd_2	29	-12	54	4	57	5	44	0.55	14.51
E	bp_4	13	-21	72	-1	61	-13	44	0.61	12.87
	bp_5	26	-21	83	5	52	-11	44	0.68	10.70
	kp_1	25	-33	83	-6	51	-23	44	0.52	15.78
	kp_2	32	-22	88	5	56	-12	44	0.68	12.09
Mean		36	-9	68	5	63	1	44	0.62	11.91

2. L243-245: After heavy rainfall events, precipitation isotopes may become depleted, and in addition to the contribution of high-altitude water vapor, potential mechanisms may include enhanced convective processes leading to increased water vapor mixing, reduced evaporation of raindrops during their descent, and changes in air mass trajectories and water vapor sources. The relative contributions and magnitudes of these mechanisms still require further analysis.

Response: We agree with the reviewer that multiple processes may contribute to isotopic depletion following heavy rainfall events. In the revised manuscript, we have expanded our explanation to explicitly include enhanced convective processes, reduced sub-cloud evaporation (evaporation of raindrops during descent), and changes in air mass trajectories. Furthermore, as suggested, we have acknowledged that while identifying these mechanisms is important, quantifying their relative contributions requires further analysis beyond the scope of this study.

Revised manuscript text: This depletion is likely driven by multiple mechanisms beyond only the input of high-altitude water vapor. These include enhanced convective processes leading to increased water vapor mixing, reduced evaporation of raindrops during their descent, and changes in air mass trajectories and water vapor sources. Collectively, these factors drive the distinct isotopic depletion observed, they collectively reflect the significant impact of intense rainfall on the local hydrological cycle.

3. L245-248: Under the influence of continental air masses, precipitation isotope values may indeed be relatively high, but "evaporation" may not be the primary cause. More critical factors likely include low precipitation amounts, short air mass transport paths, and low temperatures, which reduce the effectiveness of isotope fractionation.

Response: We appreciate this clarification. We have revised the text to accurately reflect these mechanisms.

Revised manuscript text: In contrast, during the winter and spring months (December to April), precipitation is controlled mainly by continental air masses, with relatively higher $\delta^{18}O$ and δD values. This isotopic enrichment is attributed primarily to limited precipitation amounts and shorter water vapor transport paths, which limit the degree of isotopic depletion.

4. L253-254: Regarding the average values of precipitation isotopes, please clarify whether a simple arithmetic mean or a weighted mean was used, and note that the same applies to soil water isotopes.

Response: We clarify that arithmetic means were used for the precipitation isotope values reported in the text and shown in Figure 3. As illustrated in Figure 3, we presented the data using box plots to highlight the statistical distribution and seasonal amplitude of the isotopic signals. Consequently, we calculated the arithmetic mean to represent the central tendency of these seasonal fluctuations (as detailed in the time-series analysis in Fig. 2), providing a baseline for the background isotopic environment that the vegetation experiences throughout the year. We have updated the manuscript (Section 3.1) to explicitly state that these values are arithmetic means. Soil water samples were collected at regular temporal intervals to monitor seasonal dynamics. Therefore, the arithmetic mean accurately reflects the average isotopic condition of the soil moisture that vegetation roots are exposed to over the study period. Using arithmetic means prevents bias towards specific wet periods and allows for an unbiased representation of the temporal variability shown in the box plots.

Revised manuscript text: Fig. 3 indicates that the arithmetic average $\delta^{18}O$ value of rainfall in the study area is -6‰, and the average δD value is -35.66‰, with a wide range of variations. We utilized arithmetic means to characterize the central tendency of the seasonal isotopic fluctuations and the background isotopic signature of the study area.

5. L260-263: What is the underlying mechanism for these variations? Possible factors include isotope enrichment caused by evapotranspiration, isotope depletion resulting from precipitation input, and potentially the effects of soil water storage and mixing.

Response: We thank the reviewer for this helpful comment. We agree that the observed seasonal isotope variations in mobile soil water likely reflect a combination of evapotranspiration-driven enrichment during dry periods, dilution by precipitation inputs during wet periods, and soil water storage and mixing processes. In the revised manuscript, we have added brief clarification acknowledging these potential mechanisms. However, we note that a detailed process-based attribution of these mechanisms is beyond the scope of this study. Here, the seasonal isotopic fluctuations are primarily used as a diagnostic signal for sinusoidal fitting to estimate mean residence time (MRT) and mean transit time (MTT), rather than as a basis for mechanistic interpretation.

Revised manuscript text: These seasonal dynamics are primarily driven by the combined effects of isotopically depleted precipitation inputs (amount effect) during the wet season, evaporative enrichment during the dry season, and mixing processes within the soil profile.

6. L265: Here, it would be more appropriate to use the term "soil water line" rather than "evaporation line".

Response: We agree with the reviewer. In the revised manuscript, the term "soil water line" were used instead of "evaporation line.

7. L268-269: The manuscript mentions "relatively stronger evaporative enrichment," but when δD is depleted, it typically reflects source water influence or evaporation-induced depletion rather than enrichment; the authors should rephrase this statement and clarify the mechanisms driving the variations in $\delta^{18}O$ and δD.

Response: We thank the reviewer for this comment. The phrase "relatively stronger evaporative enrichment" does not occur at Lines 268–269, which describe soil moisture dynamics (Appendix Fig. A1c) rather than isotope behavior. Nevertheless, we conducted a full-text review and revised all relevant statements to ensure that depleted δD values are attributed to source water influence, mixing processes, or evaporation-induced depletion rather than enrichment. For example, the interpretation in Lines 286–287 has been revised accordingly to correct the description of $\delta^{18}O$–δD relationships.

Revised manuscript text: The mean $\delta^{18}O$ and δD values of xylem water were -5.99‰ and -51.12‰, respectively. The relatively depleted δD and the overall evaporation line slope of 6 suggest a deviation below the LMWL, reflecting non-equilibrium isotope effects associated with source water mixing and subsurface transport processes.

8. L293-294: It is recommended to mention here that plant water uptake may also be influenced by factors such as preferential uptake, root depth distribution, and soil water availability.

Response: We agree that simply attributing the differences to "hydrological conditions" was too broad. As suggested, we have revised the sentence to explicitly acknowledge the physiological and structural factors influencing water uptake.

Revised manuscript text: This difference indicates that the water use by vegetation is directly controlled by the hydrological conditions at different sites. Specifically, the observed spatial variability is likely driven by the interplay of soil water availability, distinct root depth distributions, and preferential uptake strategies, which collectively determine the accessible water pools at each site.

9. L355–357: MRT is typically derived from isotope-based modeling as the "mean residence time." Can it be directly used to distinguish between "root uptake delay" and "within-tree storage"? Is the author actually referring to MTT (mean transit time) here?

Response: We agree that mean residence time (MRT) and mean transit time (MTT) represent distinct hydrological processes and should be strictly distinguished. MRT, derived from isotopic amplitude damping, typically reflects the time spent in storage—i.e. linked to the storage capacity and mixing turnover time within a storage reservoir (within-tree storage). MTT is the time spent transit storage—derived from isotopic phase shifts, characterizes the advective transport time or delay from the source to the sampling point (root uptake delay). We have rewritten the relevant sentence in Section 3.2 to explicitly distinguish between the two metrics.

Revised manuscript text: Table B4 details both the MRT and MTT for different water sources utilized by trees. Here, MRT (derived from amplitude damping) characterizes the time spent in storage linked to the mixing volume and turnover time of water within the tree-source system (storage), while MTT (derived from phase shift) quantifies the time spent transiting storage; that is the lag time for water to be transported from the soil/rock source to the tree xylem (uptake delay).

10. L375-384: The MixSIAR model inherently involves uncertainty, and does the 30–54% mentioned here represent the uncertainty interval?

Response: We verify that the range "30–54%" reported in this context refers to the range of mean contribution values observed across different individual trees (i.e., spatial/individual variability), rather than the Bayesian credible interval (uncertainty) of the model for a single estimate. As illustrated in Figure 6, we calculated the source contribution for each tree individual. The values "30%" and "54%" correspond to the minimum and maximum mean contributions of mobile soil water among the sampled trees during the winter months. To avoid confusion between individual variability and model uncertainty, we have revised the sentence to explicitly state that this range represents the variation across individuals.

Revised manuscript text: As shown in Fig. 6a, however, trees still exhibited relatively high uptake of mobile soil water (30-54%, mean 39%), with mean contributions ranging from 30% to 54% across individual trees (population mean 39%).

11. L400: MRT represents a statistical mean reflecting the average turnover rate of a water pool, and it is debatable whether it can be directly equated to "how much seasonal precipitation a water body can store and release precisely" The concept and applicability of MRT should be clarified in the manuscript to avoid potential misunderstandings.

Response: We thank the reviewer for this important clarification regarding the interpretation of MRT. We fully agree that MRT represents a statistical, isotope-based indicator of water turnover timescales and should not be equated with a precise quantification of how much seasonal precipitation a water body can store or release. In the revised manuscript, we have revised the interpretation of long MRT values to emphasize their role as indicators of water persistence and renewal timescales, rather than as direct measures of storage volume or release dynamics. For example, we now describe the long MRTs (169–303 days) observed in soil-filled fractures (⩾20 mm) at sites C and D as reflecting slowly renewed fracture water pools with long persistence times, which can maintain water availability across seasons and potentially alleviate early-season soil water deficits, rather than explicitly storing and releasing seasonal rainfall. Similarly, the use of fracture water with MRTs up to 128 days by ts$_6$ is now interpreted as indicating access to relatively stable, long-residence water pools, consistent with its large size and deep rooting system, rather than as a direct measure of within-tree storage or uptake delay. In contrast, smaller individuals at site E are described as relying more strongly on shallow soil water due to limited access to such persistent fracture water pools. Corresponding revisions have been made in the Results and Discussion sections to clarify the conceptual meaning of MRT and to ensure that interpretations focus on effective water availability and turnover timescales, thereby avoiding potential misunderstandings about precise storage and release processes.

Revised manuscript text: Table 3 shows that soil-filled fractures (≥20 mm) at C&D have MRTs as long as 169-303 days (mean 212 days), indicating the presence of slowly renewed fracture water pools with long persistence times, which can maintain water availability across seasons and potentially alleviate early-season soil water deficits. Additionally, Table 4 indicates that ts6 uses fracture water with a residence time of up to 128 days, demonstrating its capacity to access stable, long-residence water for transpiration. As a large tree with an extensive and deep root system, ts$_6$ efficiently exploits deep fracture water. In contrast, smaller individuals at site E (bp$_5$, kp$_{1-2}$) receive lower contributions from rock water (9-12%), relying more on shallow soil water (< 50 cm depth). Collectively, these findings suggest that long-residence rock fracture water functions as a critical 'transitional reservoir', providing critical water to support tree budding and transpiration at the onset of the growing season.

12. L461: Lc-excess primarily reflects the intensity of water evaporation and the characteristics of water recharge, nor can it be directly used to indicate water storage time.

Response: We agree with the reviewer. In the revised manuscript, we have corrected our interpretation to align with these physical mechanisms. We have removed the reference to "storage time" and instead explained the isotopic patterns as follows:

Revised manuscript text: Our study reveals significant isotopic variability in fracture water across different depths and fracture apertures (Figs. A4a and A4b). In the 0-200cm depth range, the Lc-excess values of fracture water are close to 0‰, with many values even falling below 0‰, reflecting the influence of recent rainfall inputs coupled with kinetic fractionation due to near-surface evaporation. Conversely, deep fracture water at depths greater than 200 cm typically has Lc-excess values above 0‰. This distinct isotopic signature suggests that deep fracture water is largely decoupled from surface evaporative processes, likely originating from rapid infiltration events that preserve the initial precipitation signal. Additionally, the aperture of the fractures also significantly affects the isotopic characteristics of the water. Fracture water with apertures between 0.5 and 2 mm exhibits a wide range of δD and $\delta^{18}O$, exceeding the isotopic variation range of xylem water in vegetation, indicating that these small storage volumes are highly sensitive to mixing and variable evaporative fractionation. Meanwhile, fracture water with apertures between 10 and 38 mm has isotopic values within the range of xylem water, and its Lc-excess is less than 0‰—closer to xylem water. This similarity suggests that these larger fractures store water that has undergone evaporative enrichment similar to soil water, thereby serving as a primary and stable water source for vegetation.

Minor Comments

1. Fig. 1 requires improvement, with more detailed information on the study area and sampling locations.

Response: We have substantially improved Figure 1 to provide a high-resolution characterization of the sampling locations and their specific environmental contexts.

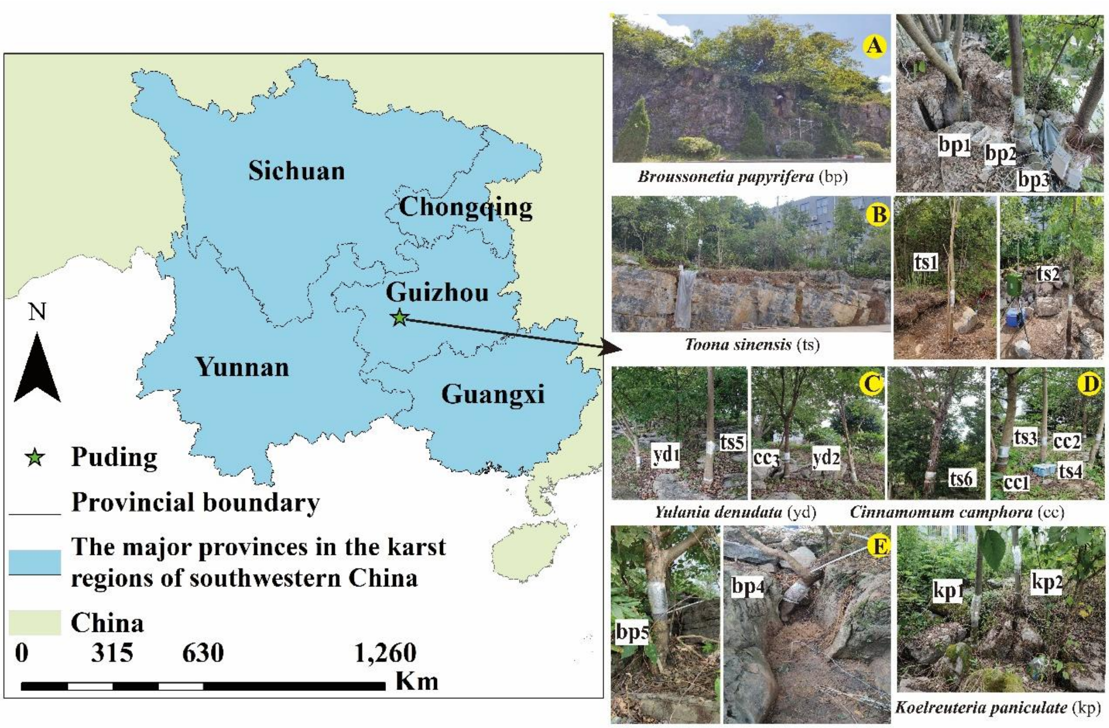


Figure 1. The study area and five sampling sites.

2. Fig. 2 has low readability, and splitting it into two panels for meteorological and isotope data is recommended.

Response: We thank the reviewer for this suggestion. In the revised manuscript, Fig. 2 has been reorganized by separating meteorological variables and isotope data into two panels to enhance readability.

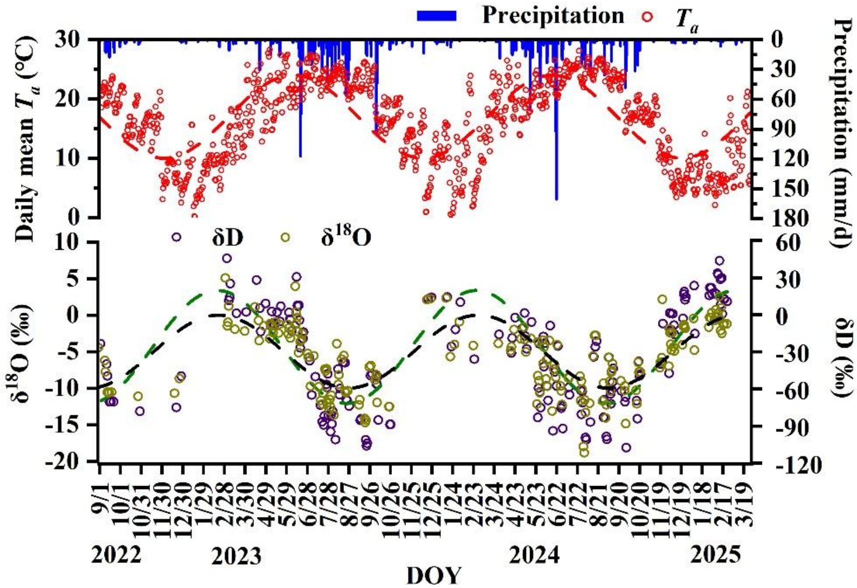


Figure 2. Temporal variations in stable isotopes of precipitation (δD and $\delta^{18}O$), rainfall amount, and daily average temperature.

3. L253: Does the term "precipitation" in the manuscript refer exclusively to rainfall, and if not, please clarify the type of precipitation.

Response: We verify that precipitation in this study refers exclusively to rainfall. The study area is located in a subtropical monsoon climate zone (mean annual temperature of 15.1°C), where solid precipitation (e.g., snow) is negligible. In Section 2.1, we added: "Precipitation in this region occurs exclusively in the form of rainfall."

4. Fig.3 lacks a legend indicating rain water.

Response: We agree and added a clear legend indicating rainwater in Fig. 3 in the revised manuscript.

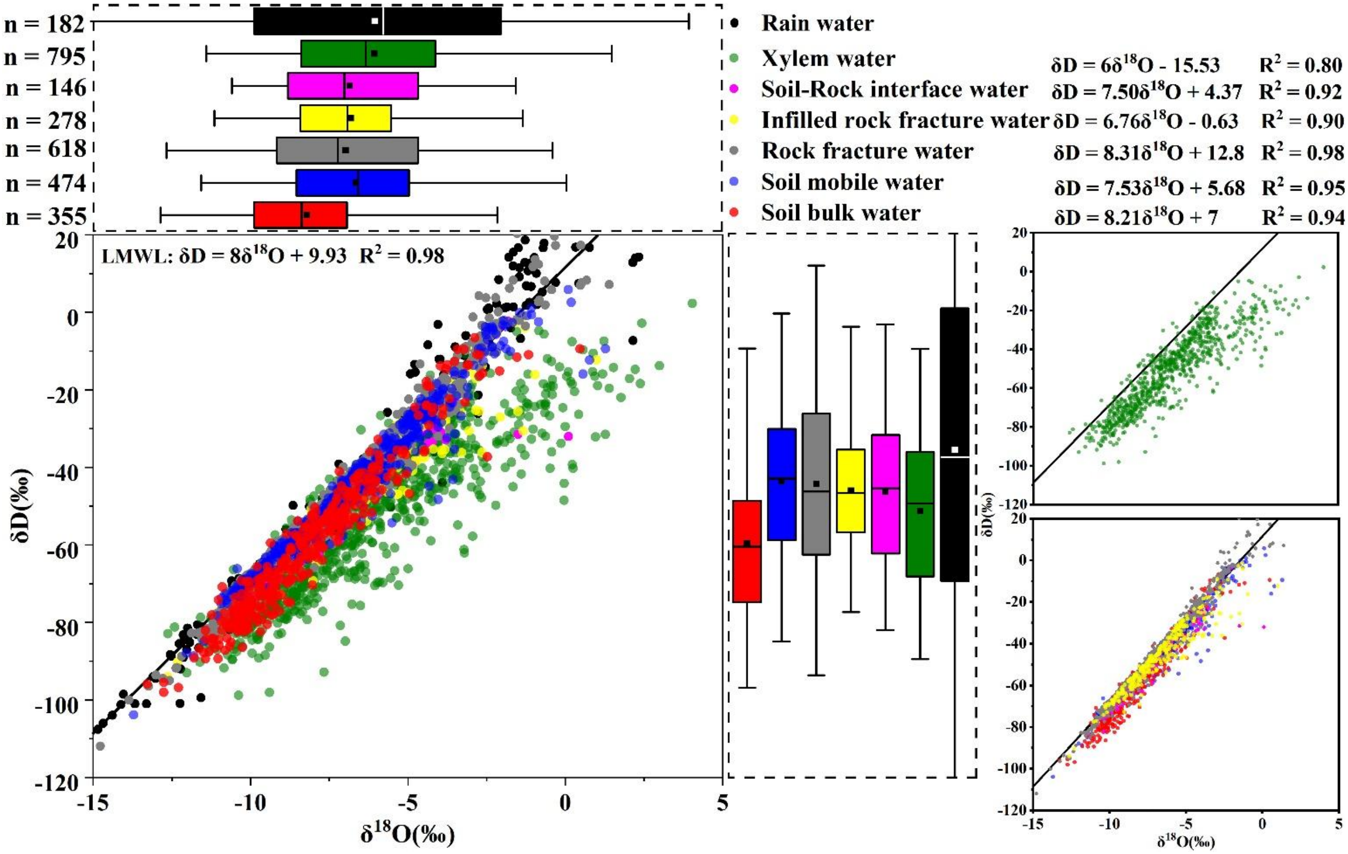


Figure 3. δD-δ^{18}O relationship diagram for different water bodies during various periods.

5. L264-265: The statement "average δD is between 59.61‰" appears to be a error.

Response: We thank the reviewer for identifying this error. The numerical value has been corrected in the revised manuscript.

6. It is recommended to use colors with higher contrast in Fig. 7 for clearer display of the comparison results.

Response: Figure 7 has been revised using colors with higher contrast to improve visual clarity.

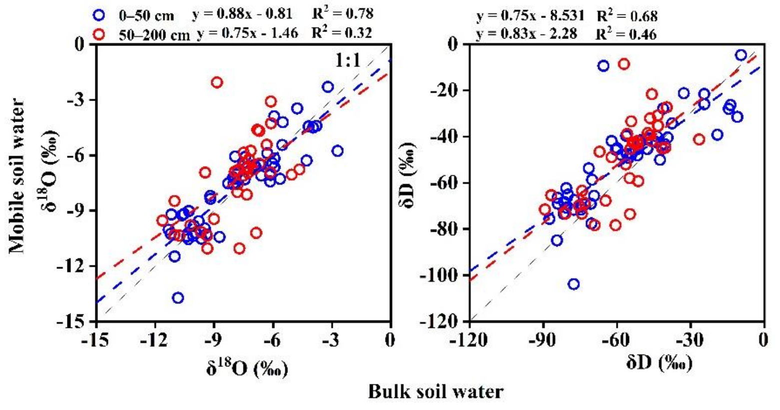
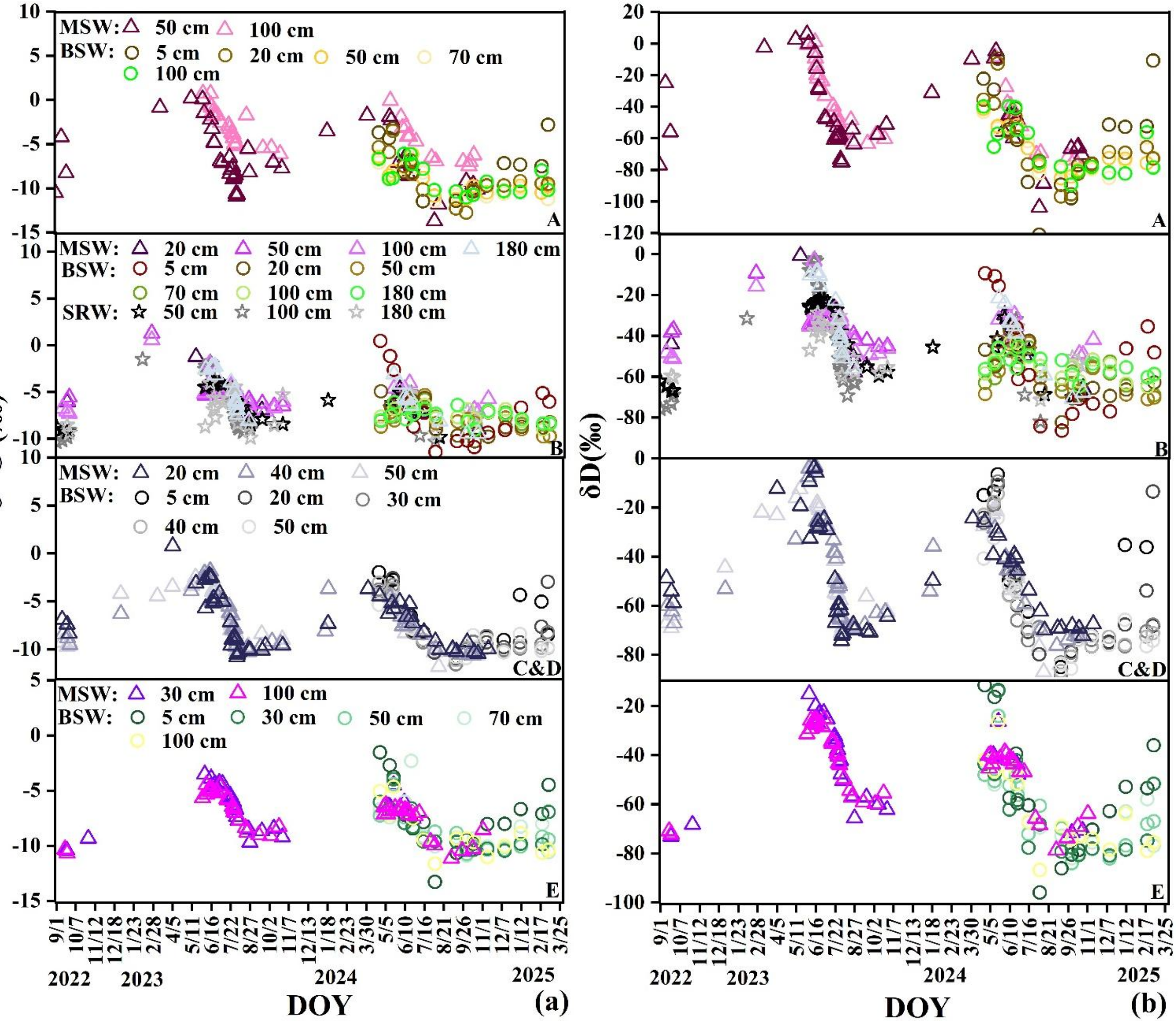


Figure 7. Isotopic comparisons (δD and $\delta^{18}O$) between bulk soil water and mobile water across soil depths.

7. Check the legends of Fig. A1 and Fig. A2 for accuracy, and ensure the readability of the figures. Adjust the legend and text sizes if necessary.

Response: We have carefully checked and revised Figures A1, A2, and A3 to ensure accuracy and readability. Specifically, we have: (1) Increased font sizes for all axis labels, legends, and text to improve visual clarity, (2) Optimized the figure layout and legends to prevent overlapping and ensure all data points are clearly distinguishable, and (3) Verified the accuracy of the symbols and descriptions in the legends.



MSW: 50 cm 100 cm
BSW: 5 cm 20 cm 50 cm 70 cm 100 cm
MSW: 20 cm 50 cm 100 cm 180 cm
BSW: 5 cm 20 cm 50 cm 70 cm 100 cm 180 cm
SRW: 50 cm 100 cm 180 cm
MSW: 20 cm 40 cm 50 cm
BSW: 5 cm 20 cm 30 cm 40 cm 50 cm
MSW: 30 cm 100 cm
BSW: 5 cm 30 cm 50 cm 70 cm 100 cm
A
B
C&D
E
δ18O (‰)
δD(‰)
DOY
2022
2023
2024
2025
(a)
(b)

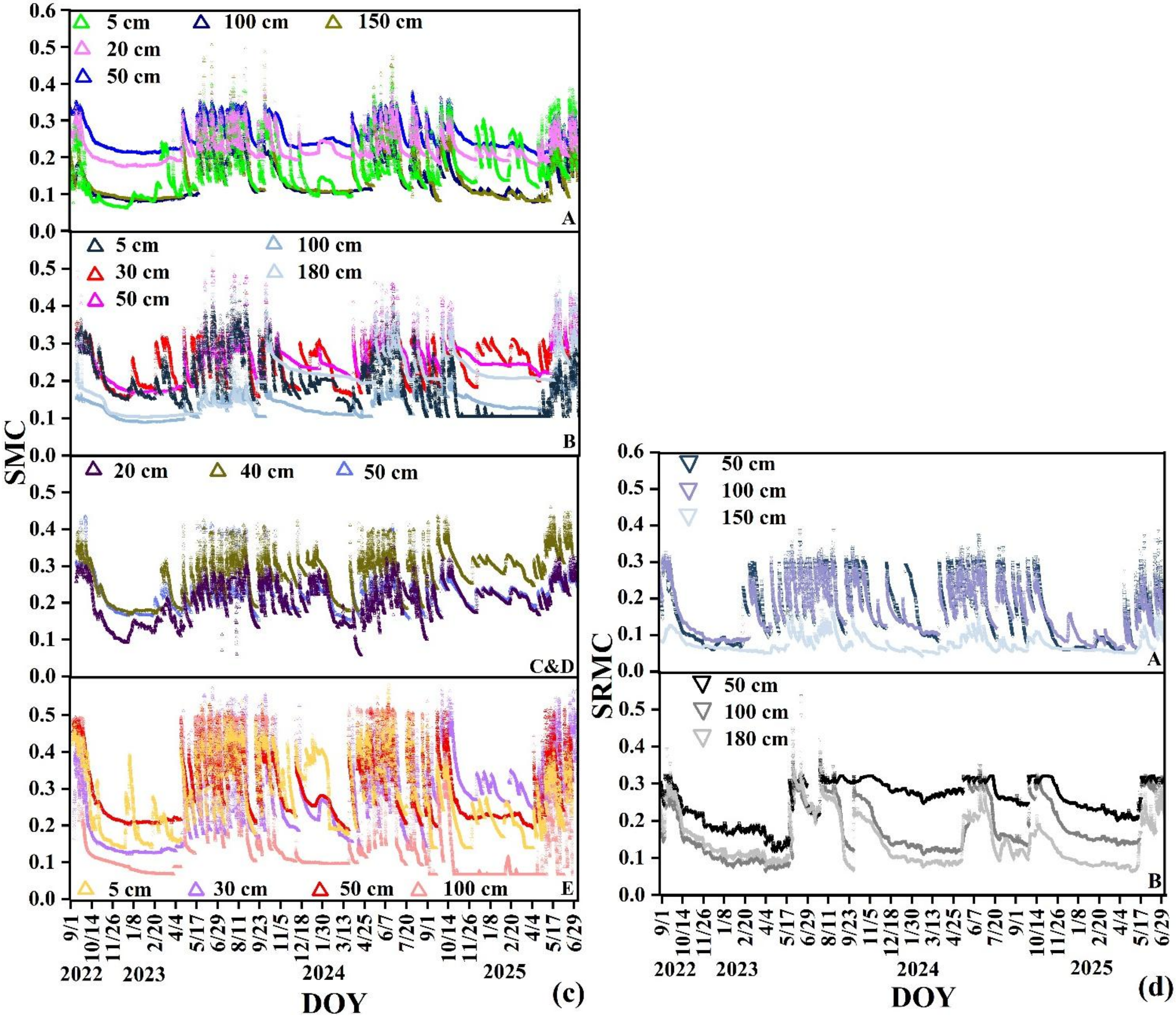
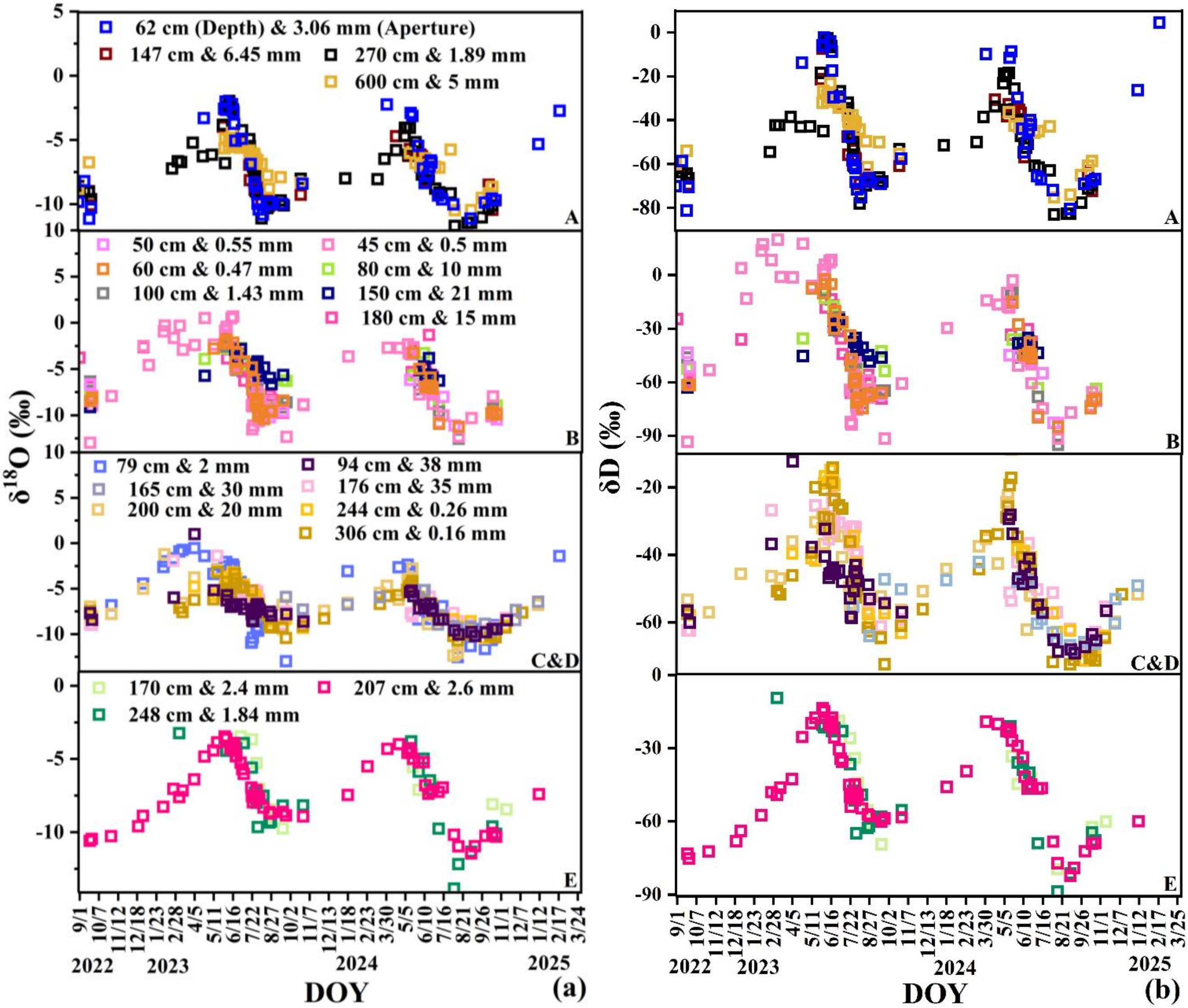


Figure A1. Dynamic variations in stable isotopes of soil water at different depths at sites (A-E): (a) $\delta^{18}O$ and (b) δD, and moisture content: (c) and (d). Mobile soil water (MSW), bulk soil water (BSW), soil-rock interface water (SRW), soil moisture content (SMC), soil-rock interface moisture content (SRMC).


62 cm (Depth) & 3.06 mm (Aperture)
147 cm & 6.45 mm
270 cm & 1.89 mm
600 cm & 5 mm
50 cm & 0.55 mm
45 cm & 0.5 mm
60 cm & 0.47 mm
80 cm & 10 mm
100 cm & 1.43 mm
150 cm & 21 mm
180 cm & 15 mm
79 cm & 2 mm
94 cm & 38 mm
165 cm & 30 mm
176 cm & 35 mm
200 cm & 20 mm
244 cm & 0.26 mm
306 cm & 0.16 mm
170 cm & 2.4 mm
207 cm & 2.6 mm
248 cm & 1.84 mm
A
B
C&D
E
δ18O (‰)
δD (‰)
DOY
2022
2023
2024
2025
(a)
(b)

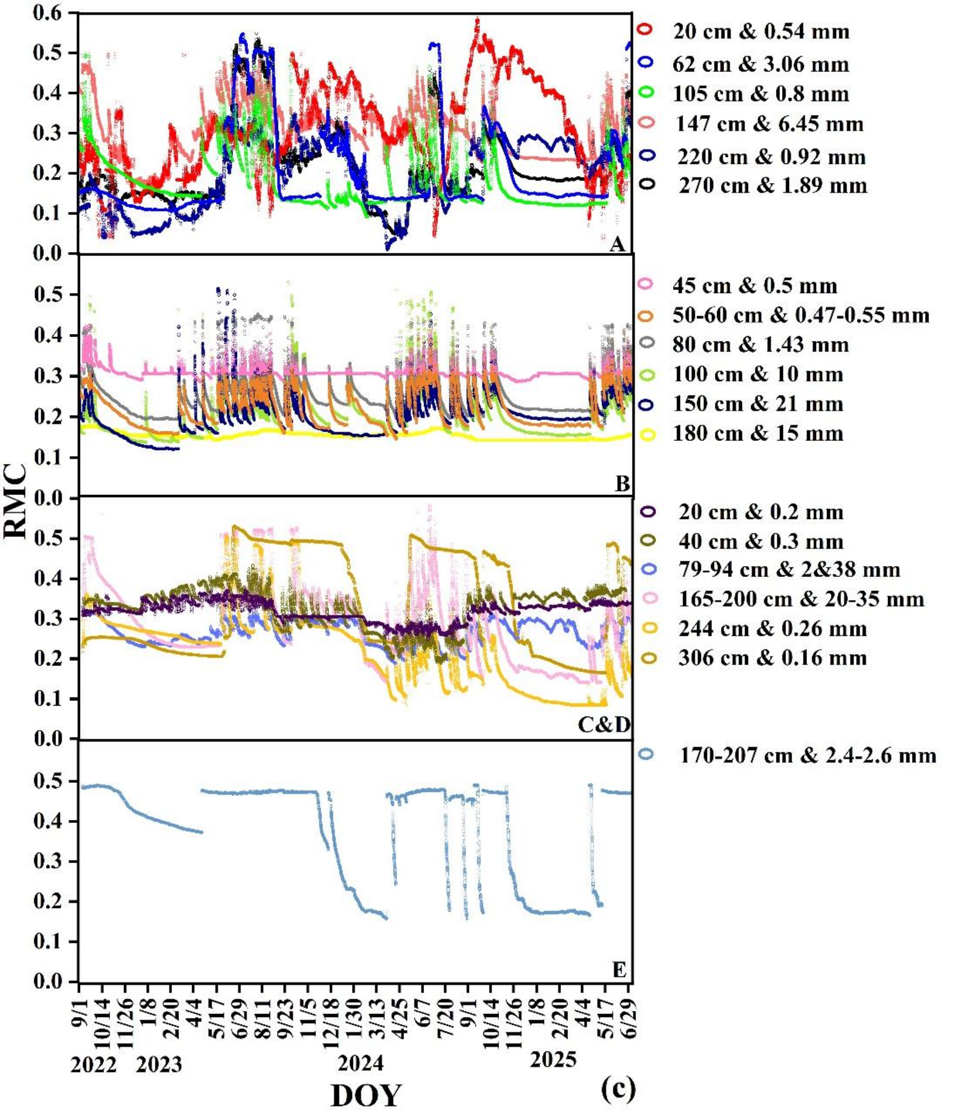


Figure A2. Dynamic variations in stable isotopes of rock fracture water at different depths / apertures at sites (A-E): (a) $\delta^{18}O$ and (b) δD, and moisture content: (c).

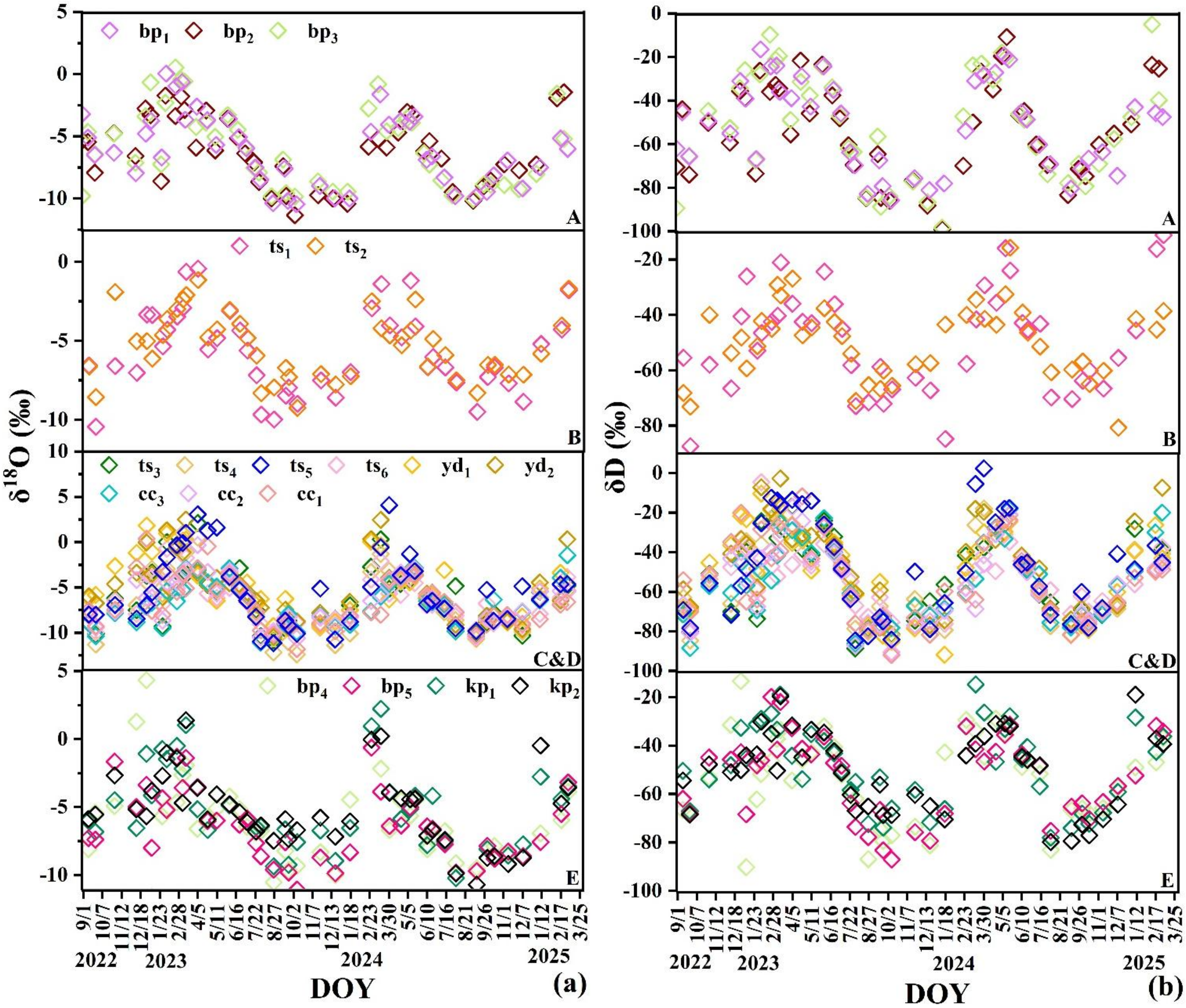


Figure A3. Dynamic variations in stable isotopes of xylem water (δD and $\delta^{18}O$) in different trees at sites (A-E).

8. Some of the parameters in the supplementary tables

Response: We thank the reviewer for noting this issue. We have enriched the supplementary tables to provide a more comprehensive dataset and ensure statistical rigor. Specifically, we added the number of samples, R^2, and standard error to Tables B1–B4. We also incorporated detailed sampling information into Tables A1 and A2. Furthermore, Table A3 now includes detailed soil depth and fracture aperture data for each sampled tree to explicitly support the micro-habitat analysis.

Title: The role of rock fractures on tree water use of water stored in bedrock: Mixing and residence times

Author(s): Xiuqiang Liu, Xi Chen, Zhicai Zhang, Weihan Liu, Tao Peng, and Jeffrey J. McDonnell

MS No.: egusphere-2025-3937

MS type: Research article

Reviewer 2:

Comments on egusphere-2025-3937

This manuscript presents a valuable contribution to understanding the role of rock fractures in the seasonal dynamics of tree water use in karst environments. By using stable isotope analysis and a Bayesian mixing model, the authors provide significant insights into how different water sources, including mobile and bulk soil water and rock fracture water, support tree transpiration under varying seasonal conditions. The findings hold potential value for ecohydrological modeling and karst ecosystem restoration. However, the manuscript requires substantial revisions to meet the publication standards of Hydrology and Earth System Sciences (HESS). The current version lacks clarity in several sections, and the analysis, while promising, needs to be more integrated and quantitatively robust. Below are the detailed comments:

Response: We sincerely thank the reviewer for the thorough and constructive evaluation of our manuscript. We appreciate the positive assessment of the potential value of this study for ecohydrological modeling and karst ecosystem restoration. We fully agree that substantial revisions are required to improve clarity, integration, and quantitative synthesis to meet the standards of HESS. Below, we respond point-by-point to all comments and clearly outline how each issue will be addressed in the revised manuscript.

1. Title and Abstract

Title: The current title, which mentions “mixing and residence times,” is somewhat vague. It would be more appropriate to focus on the fracture characteristics (e.g., aperture, infill) and their influence on plant water uptake, which is the core of the study.

Response: We agree with the reviewer's suggestion and have revised the title to place greater emphasis on fracture characteristics and their role in regulating bedrock water storage and tree water uptake, rather than on methodological descriptors. The revised title is:

"Rock fracture characteristics regulate water storage and seasonal tree water uptake in karst".

Abstract: The abstract should have consistent terminology for seasonal changes (e.g., "rain season," "growing season," "spring"). Additionally, the abstract focuses on seasonal shifts in water sourcing, but the title and introduction emphasize fracture characteristics, leading to a disconnect between the summary and the actual study focus. The abstract should reflect the true focus of the research more clearly.

Response: We agree with the reviewer's comment and have revised the abstract accordingly. Specifically, we have standardized the seasonal terminology using a growing-season framework (peak growing season, late growing season, and late non-growing season) to ensure consistency throughout the abstract. In addition, the abstract has been refocused to emphasize fracture characteristics as the primary control on bedrock water storage and tree water uptake, with seasonal shifts in water sourcing explicitly framed as outcomes of fracture-controlled storage and connectivity. The revised abstract now aligns more closely with the revised title and the main objectives of the study.

Revised manuscript text: The processes of tree water uptake in karst environments are poorly understood. One of the main challenges to improved understanding is the complex interaction between soil water and bedrock water, especially in systems characterized by structurally heterogeneous rock fractures. While some studies have highlighted the potential importance of fractured bedrock as a water source for plants, few have quantitatively assessed how fracture characteristics regulate water storage, residence times, and plant water uptake across seasons. Here, we combine stable isotope tracing, a Bayesian mixing model (MixSIAR), and hydrometric monitoring to quantify the contributions and mean residence times (MRT) of soil and rock water accessed by trees as a function of fracture properties. We use a four-compartment sampling framework that distinguishes between soil water (mobile and bulk) and rock water (fracture and infilled fracture). Our results show that fracture characteristics exert a primary control on seasonal tree water uptake patterns. During the peak growing season, mobile soil water (mean MRT = 88 days) dominates uptake (mean contribution 41%), whereas in late growing season, trees increasingly rely on bulk soil water (mean MRT = 95 days, mean contribution 55%). During the transition from the non-growing to the growing season, reliance on rock water increased in fracture-rich areas. In the reactivation stage, trees exhibited a mean rock-water contribution of 69% (mean MRT = 117 days), and in the subsequent early growing season, large trees derived up to 85% of their water from rock, primarily from soil-filled fractures with apertures >10 mm that act as seasonal storage reservoirs with prolonged residence times (MRT = 84–303 days). Trees preferentially access short-MRT sources under wet conditions and shift to longer-MRT pools during dry periods, demonstrating that seasonal water-use strategies are strongly regulated by fracture-controlled storage and connectivity. This study demonstrates that fracture characteristics play a central role in regulating rock water storage and tree water uptake in karst systems, providing new insights into vegetation resilience in structurally complex landscapes and implications for water resource management under changing climatic conditions.

2. Introduction

MRT and MTT: The introduction lacks a comprehensive review of the research progress related to Mean Residence Time (MRT) and Mean Transit Time (MTT) methods. The authors should discuss these methods more thoroughly, including their advantages, disadvantages, and how they have been applied in similar contexts, particularly in complex karst environments. This will help readers understand the relevance of the methods used in this study.

Response: We thank the reviewer for this important suggestion. In the revised Introduction, we have substantially expanded the discussion of MRT and MTT to clarify their conceptual meaning, methodological strengths, and known limitations. We now explicitly distinguish MRT as a metric describing storage and mixing behavior, and MTT as a descriptor of transport velocity and response time. We also discuss why applying these isotope-based methods in karst systems is challenging due to fracture-controlled heterogeneity, while emphasizing their value when applied to specific water pools (e.g., soil matrix vs. fracture water). These revisions are intended to better justify the relevance and appropriateness of MRT and MTT for investigating seasonal water storage and plant water availability in fractured karst systems.

Revised manuscript text: However, beyond mere source attribution, quantifying the temporal dynamics of water movement is essential for characterizing subsurface storage. Metrics such as Mean Residence Time (MRT) and Mean Transit Time (MTT) have been widely employed to estimate catchment water storage durations and the temporal lag between precipitation input and plant uptake (McGuire et al., 2002; Asadollahi et al., 2020; Liu et al., 2024b). While MRT reflects the storage capacity and mixing volume of a reservoir, and MTT characterizes the transport velocity, their application in complex karst environments remains challenging. Unlike homogeneous soils where these methods are effective (Liu et al., 2024b; Stewart and McDonnell, 1991), the high heterogeneity of karst fracture networks creates a dual-domain system characterized by rapid conduit flow and slow matrix storage. This complexity confounds standard residence time estimations (Hartmann et al., 2014; Zhang et al., 2021). Nevertheless, applying MRT and MTT analysis to specific karst water pools (e.g., fracture vs. matrix) offers a unique opportunity to unravel the temporal disparities that drive plant water availability.

Line 40-50: The second paragraph of the introduction lacks clear connections to the main research questions. The significance of ecohydrological separation should be more explicitly linked to the current study. The authors should clarify how their work addresses existing gaps in ecohydrological separation, particularly in karst ecosystems.

Response: The revised text now highlights that most evidence for ecohydrological separation originates from soil-dominated systems, whereas its applicability to karst landscapes with shallow, discontinuous soils remains unclear. We explicitly frame fractured bedrock as a potential extension of ecohydrological separation beyond the soil matrix, where contrasts between fast fracture flow and water retained in soil-filled fractures may create functionally distinct water pools. This revision clarifies how our study addresses a key gap in ecohydrological separation research under karst conditions.

Revised manuscript text: Conventionally, isotope tracing tools have been applied to identify when and where soil water is accessed by plants (Midwood et al., 1998; Tang and Feng, 2001; McCole and Stern, 2007; Darrouzet-Nardi et al., 2006; Wang et al., 2010; Brooks et al., 2010). Recent advances have crystallized into the "ecohydrological separation hypothesis", which posits that water contributing to plant transpiration is often distinct from the water that generates runoff or groundwater recharge (McDonnell, 2014; Brooks et al., 2010). This framework suggests the coexistence of at least two functionally distinct water reservoirs within the soil: a mobile, hydrologically connected fraction and a more strongly bound, plant-available fraction (Sprenger and Allen, 2020; Finkenbiner et al., 2022). However, empirical evidence for ecohydrological separation stems predominantly from soil-dominated ecosystems. In karst landscapes, the "soil" layer is often shallow and discontinuous, implying that separation mechanisms may fundamentally differ due to the underlying fractured bedrock. It remains unclear whether the ecohydrological separation hypothesis applies to the coupled soil-rock continuum, where the disparity between rapid fracture flow and water retained in soil-filled crevices could create a distinct form of separation critical for vegetation survival.

Line 77-79: The introduction suggests the manuscript's innovation is focused on fracture characteristics affecting plant water uptake, but the results and discussion primarily focus on seasonal shifts. The link between fracture characteristics and plant water uptake is not clearly demonstrated. The authors should emphasize the role of fractures more directly in their introduction and rewrite this section to align with the results.

Response: We thank the reviewer for pointing out this disconnection. We have revised the Introduction to clarify the mechanistic link between fracture characteristics and seasonal shifts. We now explicitly posit that the static physical properties of fractures (aperture and infill) are the drivers of the dynamic seasonal patterns we observed. By determining residence time, these fracture characteristics dictate when water is available, thereby forcing the seasonal shifts in plant water uptake.

Revised manuscript text: However, the mechanistic controls underlying plant water uptake from different fracture types remain poorly understood. Plants growing on different rock substrates may access varying amounts of available water, depending on the physical properties of the underlying fractures (Nardini et al., 2021; Querejeta et al., 2006; Zwieniecki and Newton, 1996; Nardini et al., 2024). No study that we are aware of has yet systematically examined how fracture aperture, depth, and degree of soil infill influence both the residence time of stored water and the patterns of plant water uptake. We propose that these static physical characteristics of fractures are the primary drivers of dynamic seasonal shifts in plant water use. Rather than viewing seasonal variation solely as a climatic response, we argue that the structural heterogeneity of fractures (e.g., aperture and infill) dictates the temporal availability of water (residence time), thereby forcing plants to shift sources as different reservoirs fill or deplete at different rates. These structural attributes may determine whether a fracture functions as a fast conduit, a temporary buffer, or a long-term reservoir for plant-available water.

Line 86: The manuscript focuses on a single research site, which limits its applicability. The authors should provide a justification for why this site can be considered representative of karst ecosystems or acknowledge its limitations as a case study.

Response: We acknowledge the reviewer's concern regarding the single study site. To address this, we have expanded the site description to frame the Puding station as a "natural laboratory" for studying universal critical zone processes. We highlighted that its "shallow-soil, fractured-bedrock" structure is representative not only of Southwest China’s karst but also analogous to Mediterranean carbonate terrains and other global fractured rock environments where vegetation relies on rock moisture.

Revised manuscript text: We focus on a site in southwest China’s karst region, characterized by a subtropical monsoon climate. Ecologically, the site is dominated by mixed evergreen and deciduous broad-leaved secondary forests, which represent the typical vegetation recovery following karst rocky desertification in this region. Beyond its specific karst features, the Puding station serves as a natural laboratory for studying hydrological processes in shallow-soil, fractured-bedrock ecosystems globally. The site typifies complex Critical Zones where regenerating vegetation grows on thin, discontinuous soils overlie highly permeable bedrock (Zhang et al., 2019; Jiang et al., 2020), ultimately increasing the frequency of drought events (Xu et al., 2023; Wang et al., 2019). This bio-geological structure mirrors not only Mediterranean carbonate terrains but also other fractured rock environments where vegetation relies on rock moisture to survive seasonal drought(Wang et al., 2019; Chen et al., 2011; Carrière et al., 2020). Despite the hydrological challenges, the structure of the soil-rock system can modulate local water storage; in areas where the epikarst possesses stronger water-holding capacity, the combined soil-fracture system retains both water and nutrients, offering critical support to maintaining the stability and sustainability of these ecosystems (Wang et al., 2024). However, the mechanistic extent to which this structural heterogeneity within the fractured bedrock dictates the partitioning of subsurface water resources and subsequently drives the water uptake patterns and survival of the overlying vegetation remains to be systematically unraveled.

3. Materials and Methods

Sampling Design: Key details regarding the sampling design should be provided in a table (e.g., tree species, number of individuals, DBH, root zone depth, and sampling replications). More details on how the sampling protocol accounts for site heterogeneity are needed.

Response: We agree with the reviewer that the sampling design should be presented more clearly. In the revised manuscript, we have added Table A1–3, which summarize the water, soil and tree-based sampling design at all study sites, including tree species, DBH, root-zone depth, and root-zone soil-rock characteristics. More detailed descriptions of vegetation characteristics and root-zone soil–rock structure at the study sites are provided in our previous study (Liu et al., 2025). The number of sampled individuals is reported in Table B4. Sampling replication is achieved by sampling multiple trees at each site as well as by repeated branch sampling within individual trees. By selecting representative trees across five sites with contrasting tree characteristics and root-zone soil-rock conditions, the sampling design accounts for site heterogeneity in tree traits and rooting environments. In addition, the description of tree xylem sampling in the Methods section has been revised to clarify the sampling procedure and replication strategy.

Revised manuscript text: The method for collecting mobile soil water and bulk soil water samples at different depths involved two preparatory steps: (1) soil boreholes were manually drilled using a soil auger to predefined discrete depths at each study site.; (2) at selected depths, soil material was removed and ceramic tensiometer tips connected to suction lysimeters were installed for the collection of mobile soil water.. The boreholes were then backfilled with the original soil to ensure proper contact and minimize disturbance. Bulk soil samples were collected at all predefined depths and bulk soil water was subsequently extracted from the collected soil samples using laboratory extraction methods. The site-specific sampling depths, sampling frequency, and sampling periods for bulk soil water and mobile soil water are summarized in Table A1. Following the conceptual framework of Sprenger et al. (2018), we distinguish between mobile soil water and bulk soil water based on their retention characteristics and accessibility under different matric suctions. Mobile soil water refers to the fraction of soil water that is weakly retained in the soil matrix and occupies larger, well-connected pores, making it accessible at relatively low matric suction and responsive to recent precipitation inputs. In this study, bulk soil water was sampled at least two days after rainfall, when gravitational water had largely drained from the soil profile. Under these conditions, the extracted bulk soil water was dominated by more strongly retained, matrix-bound water, with only a minor contribution from mobile water. To operationalize this conceptual distinction, soil water retention curves were constructed for each site and soil layer based on previously established soil hydraulic parameters (Liu et al., 2024a). Based on soil moisture distribution characteristics, site- and depth-specific upper suction thresholds associated with mobile soil water were identified for different soil types. The estimated maximum suction values corresponding to mobile soil water varied across sites and depths, reflecting differences in soil texture and hydraulic properties. Specifically, upper suction thresholds ranged from approximately 70–90 kPa at Site A (50–100 cm), 65–90 kPa at Site B (20–180 cm), 40–45 kPa at Sites C and D (20–50 cm), and 55–80 kPa at Site E. During field sampling, mobile soil water was collected using suction lysimeters operated at vacuum pressures below these site- and depth-specific upper suction thresholds to ensure that the extracted water predominantly represented mobile soil water rather than tightly bound soil water. Rock fracture water and infilled rock fracture water were distinguished based on fracture aperture and the presence of infill material observed during drilling and coring. Fractures with apertures ranging from approximately 0.1 to 10 mm generally exhibited minimal soil or sediment infill and were therefore considered to predominantly store free fracture water. Water collected from these fractures is referred to as rock fracture water. In contrast, fractures with apertures larger than approximately 10 mm were commonly partially or fully filled with soil or fine sediments. Water collected from these zones primarily represents water stored within infilled fracture material and is referred to as infilled rock fracture water. For the collection of fracture water, 26 representative fracture locations were selected based on prior field investigations (Liu et al., 2024a). At each location, boreholes were drilled and rock cores were extracted using a portable core drilling tool to directly identify fracture geometry, aperture, and infill conditions. Ceramic tensiometer tips connected to suction samplers were positioned directly within the targeted fracture zones according to the fracture classification described above. To prevent mixing of water from fractures at different depths, PVA sponges were used to hydraulically isolate individual fracture layers within the boreholes. The ceramic tips installed in soil and fracture zones were connected to sampling bottles, and a vacuum pump was used to apply negative pressure for water extraction (Figure A1). The site-specific sampling depths, fracture apertures, sampling frequency, and sampling periods for rock fracture water and infilled rock fracture water are summarized in Table A2. At each study site, representative trees were selected for xylem water sampling. Tree physiological traits and root-zone soil-rock structural characteristics are summarized in Table A3. More detailed information on vegetation characteristics and root-zone soil-rock structure at the study sites is provided in Liu et al. (2025). For each sampling campaign, three branches were collected from different positions of each sampled tree to provide within-tree replication. Sampling was conducted from September 2022 to March 2024, with an average sampling frequency of approximately two to three times per month. The bark and phloem were removed immediately after sampling, retaining only the xylem tissue, and samples were promptly sealed in airtight containers prior to laboratory analysis. Precipitation samples were collected during individual rainfall events using a standard precipitation collector installed at 1.5 m above ground level to minimize splash contamination and evaporation effects. The collector was placed in an open area, away from buildings and vegetation, to avoid external contamination. From September 2021 to March 2025, a total of 182 precipitation samples were collected. All soil and xylem samples were stored frozen, while soil water, rock water, and rainwater samples were refrigerated for storage.

Table A1. Summary of soil moisture monitoring and soil water sampling design across study sites.

Category	Soil moisture monitoring	Bulk soil sampled	Mobile soil water sampled
Dates	Sep 2022–Jun 2025	Apr 2024–Mar 2025	Sep 2022–Nov 2024
Frequency	30 min	Dry season: once per month; rainy season: 1–2 times per month	Dry season: once per month; rainy season: 1–4 times per month

Category		Soil moisture monitoring	Bulk soil sampled	Mobile soil water sampled
Depths at defferent sites (cm)	A	5, 20, 50, 100, 150	5, 20, 50, 70, 100, 150	50, 100
	B	5, 20, 50, 100, 180	5, 20, 50, 70, 100, 180	20, 50, 100, 180
	C & D	5, 20, 40, 50	5, 20, 30, 40, 50	20, 40, 50
	E	5, 30, 50, 100	5, 30, 50, 70, 100	30, 100

Table A2. Summary of rock moisture monitoring and rock water sampling design across study sites.

Category		Rock moisture monitoring	Rock water sampled
Dates		Sep 2022–Jun 2025	Sep 2022–Mar 2025
Frequency		30 min	Dry season: once per month; rainy season: 1–4 times per month
Depths at defferent sites (cm)	A	20, 62, 105, 147, 220, 270	62, 147, 270, 600
	B	45, 50, 60, 80, 100, 150, 180	45, 50, 60, 80, 100, 150, 180
	C & D	20, 40, 79, 94, 165, 176, 200, 244, 306	79, 94, 165, 176, 200, 244, 306
	E	170, 207	170, 207, 248

Table A3. Summary of tree-based sampling design and root-zone characteristics across study sites.

Site	Tree number	Species	Characteristics of root zone			Characteristics of trees			
			Soil depth (cm)	Soil volume (m^3)	Fracture volume (m^3)	Height (m)	DBH (cm)	Canopy area (m^2)	Sapwood area (cm^2)
A	bp_1	*Broussonetia papyrifera* (L.) L'Hér. ex Vent.	200	1.68	1.30	7.00	29.60	62.83	499
	bp_2		200	0.67	0.52	7.00	12.80	25.04	82.60
	bp_3		200	1.26	0.98	7.00	22.00	47.12	219
B	ts_1	*Toona sinensis* (A.Juss.) M.Roem.	43	1.12	0.04	5.50	5.40	1.30	18.36
	ts_2		22	0.42	0.05	5.80	5.80	1.51	19.23

Site	Tree number	Species	Characteristics of root zone			Characteristics of trees			
			Soil depth (cm)	Soil volume (m^3)	Fracture volume (m^3)	Height (m)	DBH (cm)	Canopy area (m^2)	Sapwood area (cm^2)
C	ts$_5$	*Toona sinensis*	16	0.12	0.61	11.50	10.77	14.00	34.19
	ts$_6$	(A.Juss.) M.Roem.	60	6.88	2.19	12.35	36.00	50.46	593
	cc$_3$	*Cinnamomum camphora* (L.) J.Presl.	52	0.71	0.95	7.00	11.73	21.90	59.24
	yd$_1$	*Yulania denudate*	53	0.37	0.44	6.00	9.63	10.07	38.45
	yd$_2$	(Desr.) D.L.Fu	52	1.42	0.33	7.00	12.75	7.52	16.34
D	ts$_3$	*Toona sinensis*	24	0.22	1.01	10.50	10.00	10.40	31.27
	ts$_4$	(A.Juss.) M.Roem.	60	0.32	1.33	10.50	9.50	13.70	29.52
	cc$_1$	*Cinnamomum camphora*	24	0.22	1.65	10.00	13.40	17.01	96.54
	cc$_2$	(L.) J.Presl.	30	0.68	1.50	8.00	14.39	15.47	128
E	bp$_4$	*Broussonetia papyrifera*	100	2.40	0.38	6.70	16.00	28.04	116.50
	bp$_5$	(L.) L'Hér. ex Vent.	15	0.15	0.41	6.50	13.30	30.68	87.26
	kp$_1$	*Koelreuteria paniculate*	20	0.19	0.06	7.00	8.00	4.24	30.44
	kp$_2$	Laxm.	20	0.18	0.04	5.80	6.80	2.83	23.12

Table B4. Statistics of MRT and MTT (day) for different trees at typical sites in the study area.

Site	Tree number	From mobile soil water to tree		From bulk soil water to tree		From rock water to tree		Number of samples	R^2	Standard error
		MRT_1	MTT_1	MRT_2	MTT_2	MRT_3	MTT_3			
A	bp$_1$	53	-1	58	5	47	-4	45	0.55	13.40
	bp$_2$	59	5	64	10	53	1	45	0.52	14.70
	bp$_3$	39	-8	44	-3	31	-12	45	0.57	14.41

Site	Tree number	From mobile soil water to tree		From bulk soil water to tree		From rock water to tree		Number of samples	R^2	Standard error
		MRT_1	MTT_1	MRT_2	MTT_2	MRT_3	MTT_3			
B	ts_1	14	0	38	-13	79	3	44	0.52	13.96
	ts_2	40	-7	94	-3	101	-3	44	0.60	10.72
C&D	ts_3	18	-9	60	8	54	7	44	0.63	10.29
	ts_4	22	-10	48	6	51	7	44	0.68	9.07
	ts_5	8	-9	32	7	25	7	44	0.60	10.13
	ts_6	96	2	124	18	128	19	44	0.67	7.78
	cc_1	42	-4	79	13	73	12	44	0.72	11.13
	cc_2	43	-1	80	15	74	14	44	0.72	11.18
	cc_3	45	2	68	19	71	19	44	0.77	11.91
	yd_1	37	-15	60	1	63	2	44	0.54	9.83
	yd_2	29	-12	54	4	57	5	44	0.55	14.51
E	bp_4	13	-21	72	-1	61	-13	44	0.61	12.87
	bp_5	26	-21	83	5	52	-11	44	0.68	10.70
	kp_1	25	-33	83	-6	51	-23	44	0.52	15.78
	kp_2	32	-22	88	5	56	-12	44	0.68	12.09
Mean		36	-9	68	5	63	1	44	0.62	11.91

Water Sampling Procedures: The differentiation between "mobile" and "bulk" soil water needs further clarification, particularly regarding suction ranges used in lysimeters.

Response: In the revised manuscript, we first clarified the conceptual definitions of mobile and bulk soil water following Sprenger et al. (2018). We then explicitly described how this conceptual distinction was operationalized in our study using soil water retention curves. Importantly, the reported suction "ranges" do not reflect variable or arbitrary lysimeter operation. For each soil layer at each site, a single upper suction threshold associated with mobile soil water was identified based on the corresponding soil water retention curve. Because multiple soil layers with distinct hydraulic properties were sampled at each site, these layer-specific thresholds collectively appear as a range when summarized at the site level. During field sampling, suction lysimeters were operated at vacuum pressures below the layer-specific upper suction threshold for each sampling depth. This ensured that the extracted water predominantly represented mobile soil water rather than tightly bound soil water. Bulk soil water, in contrast, was sampled at least two days after rainfall, after gravitational drainage had largely ceased, and was obtained by laboratory extraction, thereby integrating predominantly matrix-bound soil water. These clarifications have been added to the Methods section to make the differentiation between mobile and bulk soil water, as well as the rationale for the reported suction ranges, explicit and reproducible.

Revised manuscript text: Following the conceptual framework of Sprenger et al. (2018), we distinguish between mobile soil water and bulk soil water based on their retention characteristics and accessibility under different matric suctions. Mobile soil water refers to the fraction of soil water that is weakly retained in the soil matrix and occupies larger, well-connected pores, making it accessible at relatively low matric suction and responsive to recent precipitation inputs. In this study, bulk soil water was sampled at least two days after rainfall, when gravitational water had largely drained from the soil profile. Under these conditions, the extracted bulk soil water was dominated by more strongly retained, matrix-bound water, with only a minor contribution from mobile water. To operationalize this conceptual distinction, soil water retention curves were constructed for each site and soil layer based on previously established soil hydraulic parameters (Liu et al., 2024a). Based on soil moisture distribution characteristics, site- and depth-specific upper suction thresholds associated with mobile soil water were identified for different soil types. The estimated maximum suction values corresponding to mobile soil water varied across sites and depths, reflecting differences in soil texture and hydraulic properties. Specifically, upper suction thresholds ranged from approximately 70–90 kPa at Site A (50–100 cm), 65–90 kPa at Site B (20–180 cm), 40–45 kPa at Sites C and D (20–50 cm), and 55–80 kPa at Site E. During field sampling, mobile soil water was collected using suction lysimeters operated at vacuum pressures below these site- and depth-specific upper suction thresholds to ensure that the extracted water predominantly represented mobile soil water rather than tightly bound soil water.

The method for distinguishing between "rock fracture water" and "infilled rock fracture water" should be better explained. A schematic of the sampling process would be helpful.

Response: In the revised manuscript, we have clarified the distinction between rock fracture water and infilled rock fracture water by explicitly defining these two water types based on fracture aperture and infill conditions observed during drilling and coring. Specifically, fractures with apertures of approximately 0.1–10 mm typically exhibit minimal soil or sediment infill and predominantly store free fracture water, whereas fractures larger than ~10 mm are commonly partially or fully filled with soil or fine sediments and therefore store infilled fracture water. These distinctions are made during field sampling rather than inferred from isotopic composition. We have revised the Methods section. In addition, a schematic illustration (Figure A1) has been added to visually summarize the soil-rock-fracture sampling configuration.

Revised manuscript text: Rock fracture water and infilled rock fracture water were distinguished based on fracture aperture and the presence of infill material observed during drilling and coring. Fractures with apertures ranging from approximately 0.1 to 10 mm generally exhibited minimal soil or sediment infill and were therefore considered to predominantly store free fracture water. Water collected from these fractures is referred to as rock fracture water. In contrast, fractures with apertures larger than approximately 10 mm were commonly partially or fully filled with soil or fine sediments. Water collected from these zones primarily represents water stored within infilled fracture material and is referred to as infilled rock fracture water. For the collection of fracture water, 26 representative fracture locations were selected based on prior field investigations (Liu et al., 2024a). At each location, boreholes were drilled and rock cores were extracted using a portable core drilling tool to directly identify fracture geometry, aperture, and infill conditions. Ceramic tensiometer tips connected to suction samplers were positioned directly within the targeted fracture zones according to the fracture classification described above. To prevent mixing of water from fractures at different depths, PVA sponges were used to hydraulically isolate individual fracture layers within the boreholes. The ceramic tips installed in soil and fracture zones were connected to sampling bottles, and a vacuum pump was used to apply negative pressure for water extraction (Figure S1). The site-specific sampling depths, fracture apertures, sampling frequency, and sampling periods for rock fracture water and infilled rock fracture water are summarized in Table A2.

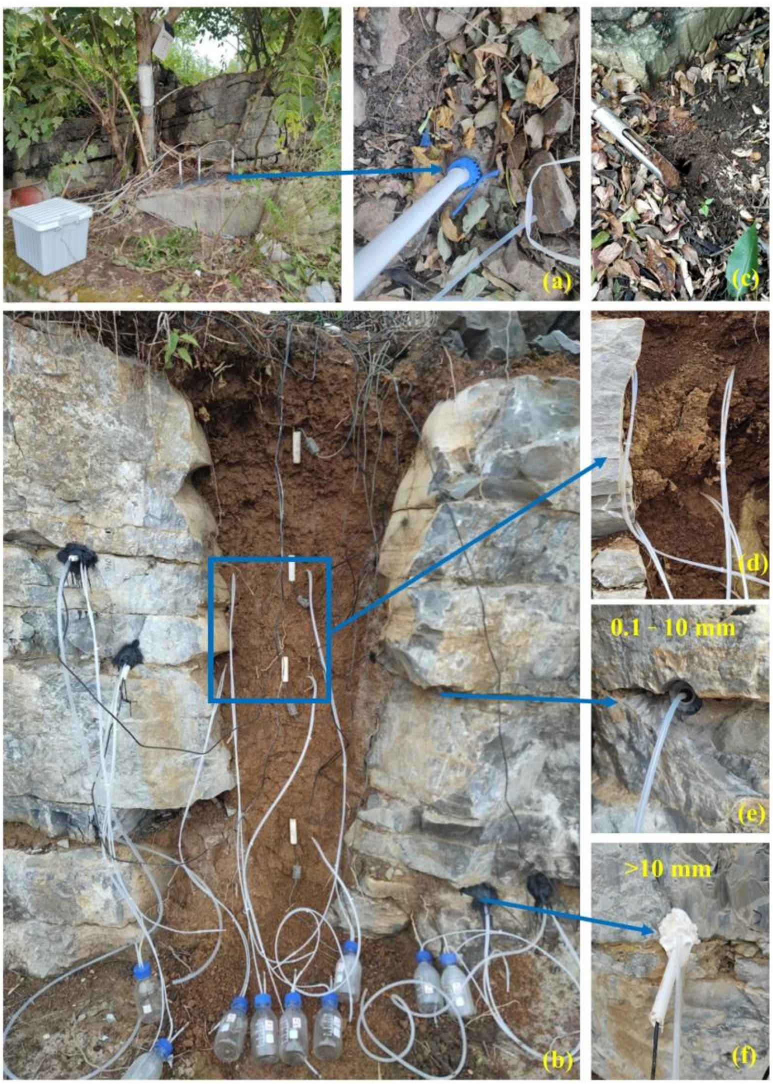


Figure S1. Field photographs illustrating soil and rock water sampling procedures. (a) Vertical boreholes drilled at sites C, D, and E with water sampling devices installed at predefined depths. (b) Horizontal boreholes drilled into exposed bedrock outcrops at sites A and B with sampling devices installed within the soil-rock profile. (c) Collection of soil samples for laboratory extraction of bulk soil water. (d) Collection of mobile soil water using suction lysimeters installed in soil layers. (e) Collection of rock fracture water from narrow fractures (aperture approximately 0.1–10 mm) with little or no soil infill. (f) Collection of infilled rock fracture water from wider fractures (>10 mm aperture) largely filled with soil or fine sediments.

Precipitation and Sensor Data: The method for collecting precipitation isotope data is missing, and details on the replication and installation of soil moisture sensors are absent.

Response: We agree that these details should be made explicit. In the revised manuscript, we have added a detailed description of the precipitation isotope sampling protocol. Details regarding the replication strategy and installation of soil moisture sensors have been clarified by explicitly referring to our previous study (Liu et al., 2025), where sensor types, installation depths, spatial replication, and data acquisition procedures are described in detail. This reference has been added to the Methods section to ensure transparency and reproducibility.

Revised manuscript text: Precipitation samples were collected during individual rainfall events using a standard precipitation collector installed at 1.5 m above ground level to minimize splash contamination and evaporation effects. The collector was placed in an open area, away from buildings and vegetation, to avoid external contamination. From September 2021 to March 2025, a total of 182 precipitation samples were collected.

Analytical Protocols: The use of two different laboratories (Tianjin and Saskatchewan) requires justification. The authors should demonstrate cross-validation of results between labs to ensure no systematic bias.

Response: The use of two laboratories reflects the long-term nature of the project and the development of international collaboration during different phases of the study. Samples collected between September 2022 and March 2024 were processed and analyzed at Tianjin University, whereas samples collected from April 2024 to March 2025 were processed and analyzed at the University of Saskatchewan. The isotope time series used for the estimation of mean transit time (MTT) and mean residence time (MRT) spans the entire period from September 2022 to March 2025 and therefore includes data analyzed in both laboratories. As shown by the precipitation isotope record (Fig. 2) and the isotopic dynamics of soil water, rock water, and xylem water (Figs. A1–A3), the isotope signals over this period exhibit smooth and continuous seasonal variations with clear sinusoidal characteristics. No discontinuities or step changes are observed at the transition between the two analytical phases, indicating good continuity and consistency between datasets obtained from the two laboratories. This temporal coherence results in stable sinusoidal fitting and low uncertainties in the estimation of MTT and MRT. In contrast, the quantitative water source partitioning is based exclusively on samples collected from April 2024 to March 2025, during which all samples were processed and analyzed at the University of Saskatchewan. In particular, bulk soil water samples were extracted and analyzed only in Canada, ensuring full internal consistency for this key water compartment. Regarding analytical instrumentation, laser-based isotope analyses of rainfall, mobile soil water, and rock water were conducted using cavity-enhanced spectroscopy systems (Picarro L2140-i and LGR OA-ICOS), which rely on comparable physical principles and are calibrated against the same international standards (VSMOW–SLAP). Analytical uncertainties were ±0.1‰ for δD and ±0.015‰ for $\delta^{18}O$ for the Picarro system, and ±2‰ for δD and ±0.8‰ for $\delta^{18}O$ for the LGR system. These instruments are widely regarded as methodologically equivalent for liquid water samples without strong organic interference. Plant and soil extracted waters were analyzed using isotope ratio mass spectrometry (IRMS) at both laboratories, which is considered the reference technique for stable isotope measurements and is less sensitive to organic contamination. The analytical reproducibility of IRMS measurements was approximately ±1.0‰ for δD and ±0.2‰ for $\delta^{18}O$, comparable between laboratories. Taken together, the phase-based analytical design, the observed temporal continuity of isotope signals across the full study period, and the use of a single laboratory for water source partitioning demonstrate that the use of two laboratories did not introduce systematic analytical bias into the interpretation of water ages or water source contributions.

In the revised manuscript, we have clarified this analytical design in the main text as follows. At the beginning of Section 2.3 (Laboratory analyses).

Revised manuscript text: Due to the long-term nature of the project and the development of international collaboration, sample processing and testing were divided into two analytical periods. Samples collected between September 2022 and March 2024 were processed and analyzed at the Ecohydrology and Water Resources Research Center and the Experimental Test Analysis Science and Technology Center, School of Earth System Science, Tianjin University. Samples collected from April 2024 to March 2025 were processed and analyzed at the University of Saskatchewan, Canada.

In Section 2.4.1 (Estimation of mean transit time and mean residence time), we have added a concluding paragraph clarifying that the isotope time series used for MTT and MRT estimation.

Revised manuscript text: The isotope time series used for the estimation of MTT and MRT spans the entire period from September 2022 to March 2025 and therefore includes data analyzed in both laboratories. As shown by the precipitation isotope record (Fig. 2) and the isotopic dynamics of soil water, rock water, and xylem water (Figs. A1–A3), the isotope signals over this period exhibit smooth and continuous seasonal variations with clear sinusoidal characteristics. No discontinuities or step changes are observed at the transition between the two analytical phases, indicating good continuity and consistency between datasets obtained from the two laboratories. This temporal coherence results in stable sinusoidal fitting and low uncertainties in the estimation of MTT and MRT.

In Section 2.4.2 (MixSIAR model), we have added a final paragraph specifying that quantitative water source partitioning is based exclusively on samples collected from April 2024 to March 2025.

Revised manuscript text: The quantitative water source partitioning using the MixSIAR model is based exclusively on samples collected from April 2024 to March 2025. All samples used for source partitioning were processed and analyzed at the University of Saskatchewan, Canada. This analytical design minimizes potential inter-laboratory variability and ensures internal consistency among water sources, particularly for bulk soil water, which was extracted and analyzed only in Canada.

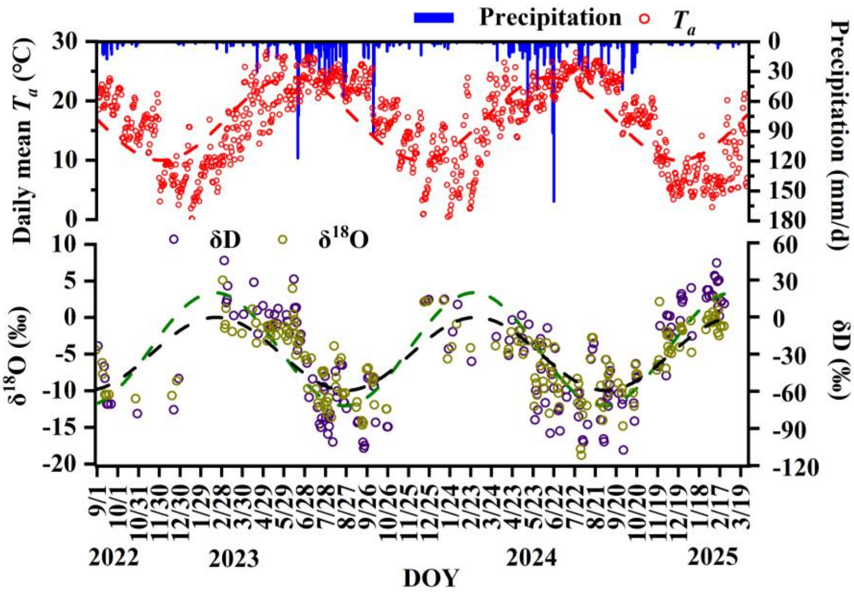


Figure 2. Temporal variations in stable isotopes of precipitation (δD and $\delta^{18}O$), rainfall amount, and daily average temperature.

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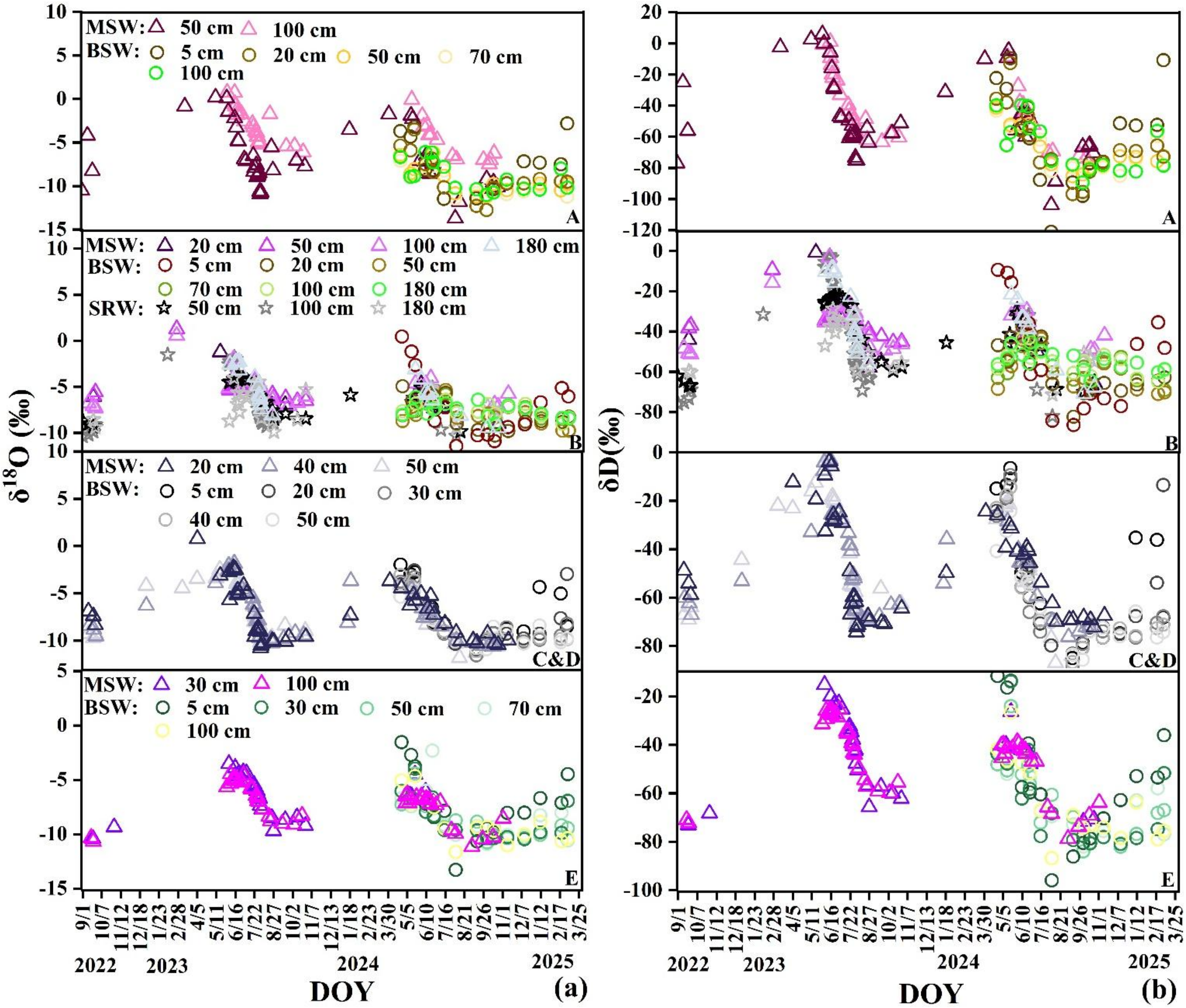


MSW: 50 cm 100 cm
BSW: 5 cm 20 cm 50 cm 70 cm 100 cm
MSW: 20 cm 50 cm 100 cm 180 cm
BSW: 5 cm 20 cm 50 cm 70 cm 100 cm 180 cm
SRW: 50 cm 100 cm 180 cm
MSW: 20 cm 40 cm 50 cm
BSW: 5 cm 20 cm 30 cm 40 cm 50 cm
MSW: 30 cm 100 cm
BSW: 5 cm 30 cm 50 cm 70 cm 100 cm
A
B
C&D
E
δ18O (‰)
δD(‰)
DOY
2022
2023
2024
2025
(a)
(b)

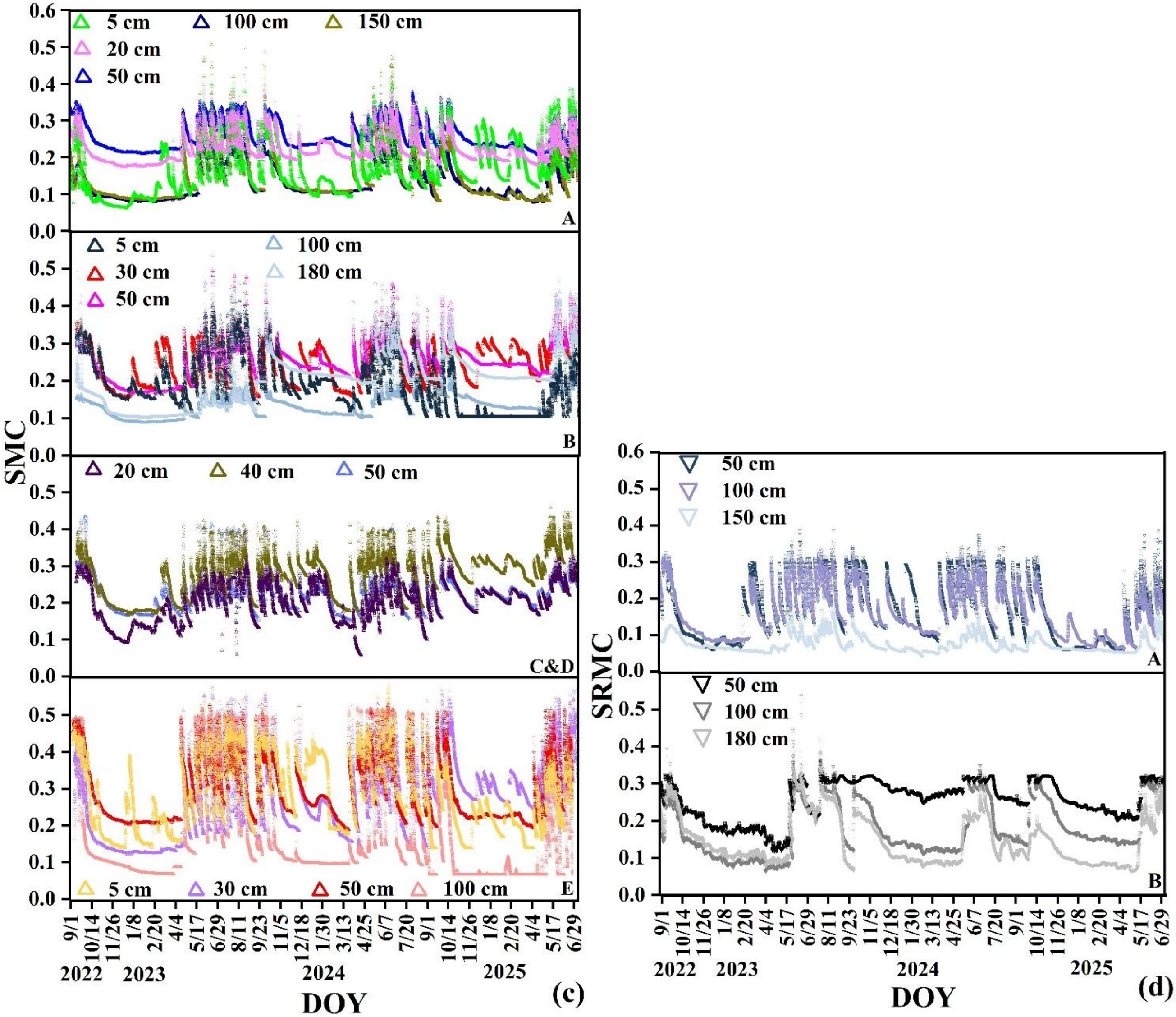
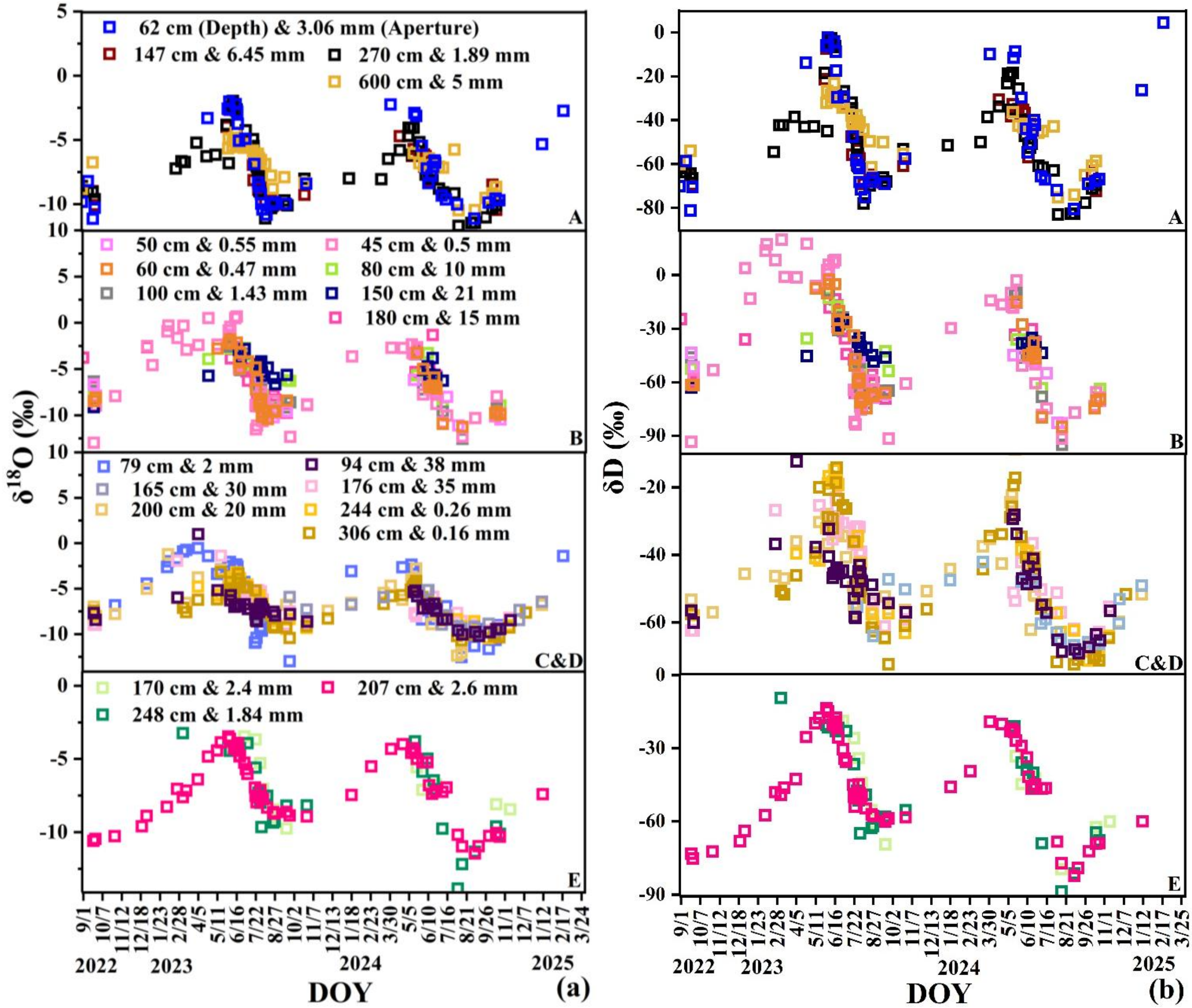


Figure A1. Dynamic variations in stable isotopes of soil water at different depths at sites (A-E): (a) δ^{18}O and (b) δD, and moisture content: (c) and (d). Mobile soil water (MSW), bulk soil water (BSW), soil-rock interface water (SRW), soil moisture content (SMC), soil-rock interface moisture content (SRMC).



62 cm (Depth) & 3.06 mm (Aperture)
147 cm & 6.45 mm
270 cm & 1.89 mm
600 cm & 5 mm
50 cm & 0.55 mm
45 cm & 0.5 mm
60 cm & 0.47 mm
80 cm & 10 mm
100 cm & 1.43 mm
150 cm & 21 mm
180 cm & 15 mm
79 cm & 2 mm
94 cm & 38 mm
165 cm & 30 mm
176 cm & 35 mm
200 cm & 20 mm
244 cm & 0.26 mm
306 cm & 0.16 mm
170 cm & 2.4 mm
207 cm & 2.6 mm
248 cm & 1.84 mm
A
B
C&D
E
δ18O (‰)
δD (‰)
DOY
2022
2023
2024
2025
(a)
(b)

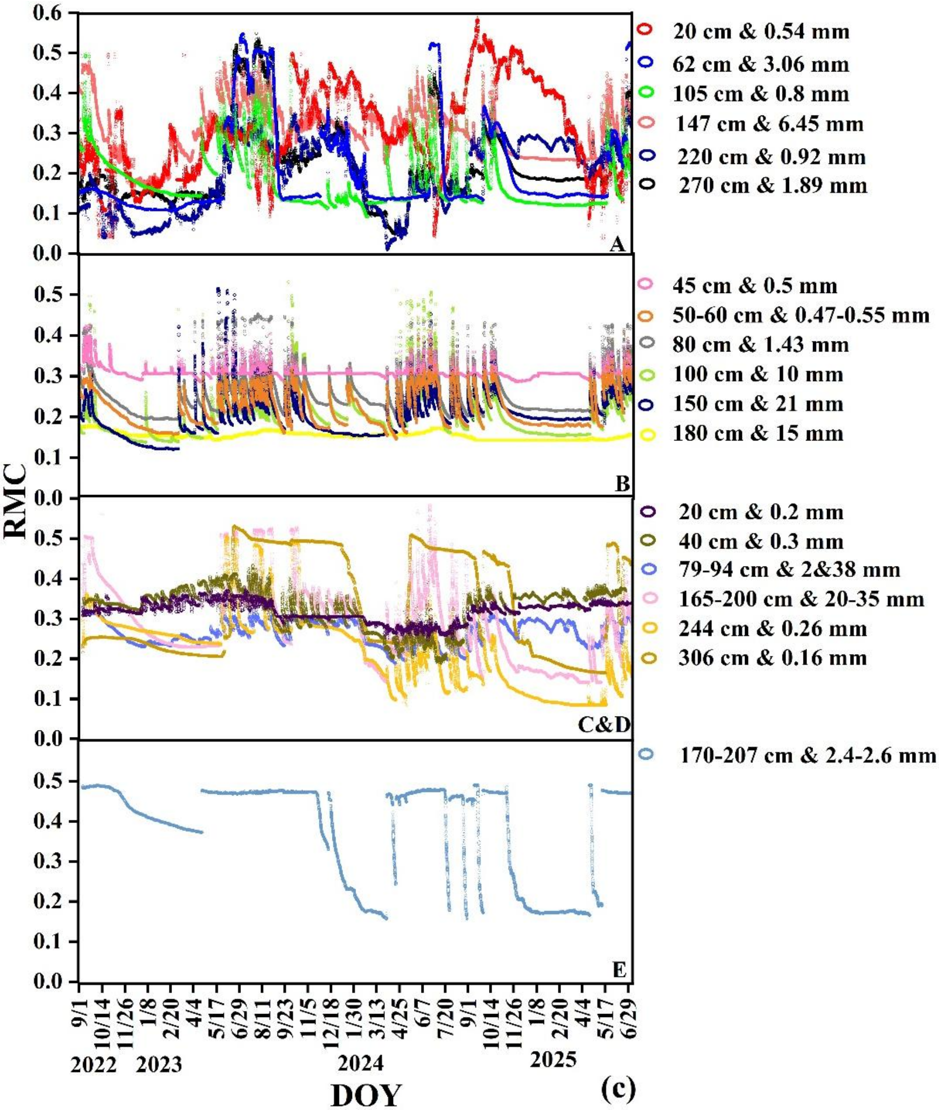


Figure A2. Dynamic variations in stable isotopes of rock fracture water at different depths / apertures at sites (A-E): (a) $\delta^{18}O$ and (b) δD, and moisture content: (c).

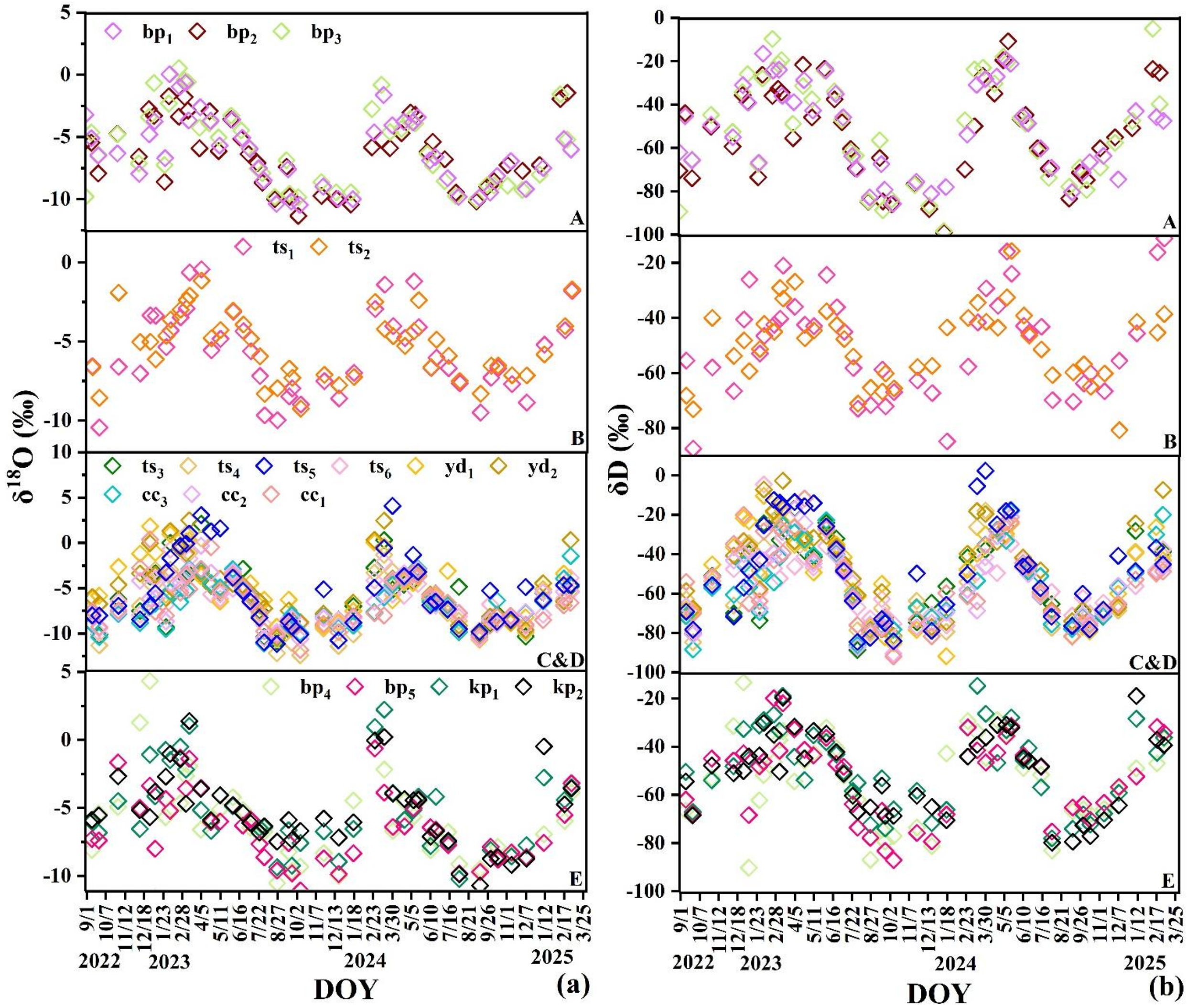


Figure A3. Dynamic variations in stable isotopes of xylem water (δD and $\delta^{18}O$) in different trees at sites (A-E).

Assumptions of MRT Method: The assumptions behind the MRT method are not discussed in the manuscript. In a complex karst system, using such methods may introduce significant uncertainties. The authors need to explain the assumptions clearly and discuss the potential sources and magnitude of uncertainty in their methodology.

Response: In the revised manuscript, we have revised the opening paragraph of Section 2.4.1 to explicitly define MRT as an effective, isotope-based measure that characterizes seasonally integrated water storage and mixing behavior, rather than a precise physical storage duration. As now stated in the text, MRT reflects the integrated effects of storage, mixing, and transport processes and is particularly suited to describing dominant seasonal storage behavior in karst environments, where flow pathways are highly heterogeneous. We further clarify that MRT is estimated using the amplitude damping approach, which assumes that seasonal isotope variability provides a coherent, integrated input signal and that attenuation of isotope signal amplitudes primarily reflects mixing and storage processes at the seasonal timescale. This framing emphasizes that the MRT method targets seasonally integrated behavior rather than short-term, event-scale dynamics that may be strongly influenced by preferential flow or fracture–matrix interactions. To address uncertainty, we now explicitly state in the revised manuscript that MRT values should be interpreted as effective or apparent residence times. Rather than defining absolute physical error bounds, the magnitude of uncertainty is evaluated through the goodness of fit of the sinusoidal models and the temporal stability of fitted parameters across water compartments. These indicators provide a practical measure of the reliability of MRT estimates in a complex karst setting. Corresponding revisions have been made in the Methods section (Section 2.4.1) to clarify the conceptual assumptions of the MRT method and to discuss its applicability and uncertainty in heterogeneous karst systems, without altering the mathematical formulation or the resulting MRT estimates.

Revised manuscript text: The mean residence time (MRT) represents an effective, isotope-based measure of the average time that water resides within a given compartment. Rather than describing a precise physical storage duration, MRT characterizes the seasonally integrated effects of storage, mixing, and transport processes. In karst environments, where flow pathways are highly heterogeneous, MRT is particularly useful for describing the dominant seasonal storage behavior of water within soil, fracture, and rock compartments. For example, soil water at 50 cm depth may retain infiltrated rainfall for a certain period before contributing to deeper flow or evapotranspiration. We estimated MRT using the amplitude damping approach (Małoszewski and Zuber, 1982; Reddy et al., 2006; Stewart and McDonnell, 1991; McGuire et al., 2002) , which interprets the attenuation of seasonal isotope signal amplitudes as a response to mixing and storage along flow pathways. This approach assumes that seasonal isotope variability provides an integrated signal of water storage and turnover at the timescale of interest, which is well suited for investigating seasonal water storage dynamics in karst systems.

Isotopic Fitting for Different Water Types: The MRT and MTT methods rely on fitting isotopic data (e.g., for precipitation, soil water, and plant water) to sinusoidal functions. However, the manuscript lacks a discussion of the isotopic fitting for different water types over the study period, and there is no assessment of the fitting quality (e.g., R-squared values). The authors should include this information to evaluate the reliability and applicability of these methods.

Response: We agree that the quality of the sinusoidal fitting for different water types should be explicitly documented to support the reliability and applicability of the MRT and MTT analyses. In the revised manuscript, we have added quantitative indicators of fitting quality for all water compartments. Specifically, we now report the coefficient of determination (R^2) and the standard error of the sinusoidal fits for mobile soil water, bulk soil water, soil-rock interface water, and tree xylem water. These metrics are summarized in the revised Appendix Tables B1–B4. Overall, the sinusoidal fitting shows satisfactory performance across water types, with R^2 values consistently greater than 0.50. Mean R^2 values are 0.64 for mobile soil water, 0.72 for bulk soil water, 0.64 for soil-rock interface water, and 0.61 for tree xylem water. Corresponding mean standard errors are 10.18‰ for mobile soil water, 10.25‰ for bulk soil water, 9.20‰ for soil-rock interface water, and 11.92‰ for tree xylem water. These results indicate that seasonal isotope variability is well captured by the sinusoidal models, supporting the use of amplitude damping which based MRT and MTT estimation. In addition, we have added a brief description in the Methods section to explain how fitting quality was evaluated and to clarify that R^2 reflects the goodness of fit of the seasonal signal, while the standard error reflects the stability of fitted parameters rather than absolute physical uncertainty.

Table B1. Statistics of MRT and MTT (day) for mobile and bulk water in different soil layers.

Site	Depth (cm)	K_h ($cm \cdot h^{-1}$)	Average moisture content	Mobile soil water					Bulk soil water				
				MRT	MTT	Number of samples	R^2	Standard error	MRT	MTT	Number of samples	R^2	Standard error
A	5	3.83	0.153	-	-	-	-	-	36	6	16	0.75	19.08
	20	3.33	0.223	-	-	-	-	-	65	16	16	0.89	11.20
	50	2.33	0.264	72	15	68	0.56	18.15	139	26	16	0.67	8.48
	70	2.18	-	-	-	-	-	-	155	28	16	0.54	8.46
	100	1.96	0.133	74	31	36	0.83	11.77	138	32	16	0.64	9.96
B	5	0.58	0.212	-	-	-	-	-	49	10	16	0.80	11.74

Site	Depth (cm)	K_h ($cm \cdot h^{-1}$)	Average moisture content	Mobile soil water					Bulk soil water				
				MRT	MTT	Number of samples	R^2	Standard error	MRT	MTT	Number of samples	R^2	Standard error
	20	0.44	0.245	63	23	23	0.61	9.35	177	31	16	0.55	9.01
	50	0.16	0.241	459	34	38	0.52	2.09	471	73	16	0.50	9.00
	70	0.17	-	-	-	-	-	-	638	82	16	0.54	6.82
	100	0.18	0.125	244	43	40	0.54	5.34	685	47	16	0.50	5.41
	180	0.10	0.182	77	24	25	0.64	10.59	708	63	16	0.53	4.84
C&D	5	4.96	0.191	-	-	-	-	-	40	6	16	0.78	17.07
	20	1.04	0.261	85	25	51	0.68	12.28	60	12	16	0.81	11.02
	30	1.04	-	-	-	-	-	-	66	9	16	0.83	13.13
	40	1.04	0.209	85	33	45	0.74	11.04	63	12	16	0.87	10.71
	50	1.04	0.209	63	20	49	0.83	11.77	95	17	16	0.93	7.18
E	5	1.42	0.309	-	-	-	-	-	47	8	16	0.83	13.63
	30	0.75	0.227	122	38	33	0.57	9.77	108	19	16	0.68	12.30
	50	0.75	0.298	-	-	-	-	-	131	27	16	0.85	8.95
	70	0.83	-	-	-	-	-	-	118	24	16	0.88	7.79
	100	0.96	0.204	144	32	48	0.50	9.84	121	17	16	0.74	9.41
Mean	51	1.39	0.217	135	29	41	0.64	10.18	196	27	16	0.72	10.25

Table B2. Statistics of MRT and MTT (day) for soil-rock interface water in different soil layers

Site	Depth (cm)	Average moisture content	MRT	MTT	Number of samples	R^2	Standard error
B	50	0.254	119	39	46	0.57	9.23
	100	0.166	21	25	35	0.85	11.69
	180	0.154	214	41	10	0.50	6.68
Mean	110	0.191	118	35	30	0.64	9.20

Table B3. Statistics of MRT and MTT (day) for fractures of different apertures and depths.

Site	Aperture (mm)	Depth (cm)	Porosity (ε_p)	K_h ($cm \cdot h^{-1}$)	Average moisture content	MRT	MTT	Number of samples	R^2	Standard error
C&D	0.16	306	1	0.09	0.354	124	31	54	0.56	11.30
C&D	0.26	244	1	1.13	0.256	118	34	43	0.63	10.80
B	0.47	60	1	3.04	0.217	57	24	44	0.72	14.04
B	0.50	45	1	3.42	0.310	23	-2	30	0.70	17.44
B	0.55	50	1	3.71	0.217	91	25	59	0.50	17.77
B	1.43	80	0.98	17	0.260	76	22	34	0.64	14.03
E	1.8	248	0.75	13	-	73	20	34	0.72	14.84
A	1.89	270	0.98	673	0.217	108	30	61	0.61	14.62
C&D	2	79	0.74	76	0.256	35	2	60	0.73	15.13
E	2.4	170	0.6	34	0.413	103	29	23	0.55	12.06
E	2.6	207	0.54	47	0.413	97	33	70	0.75	10.23
A	3.06	62	0.80	40	0.203	60	22	44	0.69	13.90
A	5	600	0.66	3496	-	182	29	47	0.50	6.21
A	6.45	147	0.55	6208	0.317	100	24	38	0.69	9.75
B	10	100	0.41	6	0.206	136	27	38	0.55	12.20
B	15	180	0.45	33	0.158	84	21	44	0.57	12.85
C&D	20	200	0.47	315	0.311	176	25	53	0.60	8.63
B	21	150	0.74	1042	0.188	198	38	25	0.55	12.20
C&D	30	165	0.49	87	0.311	303	20	25	0.54	6.90
C&D	35	176	0.74	2232	0.311	169	38	43	0.50	9.22
C&D	38	94	0.70	2746	0.256	200	24	50	0.61	6.23
Mean	9.41	173	0.74	813	0.272	120	25	44	0.61	11.92

4. Results

The Results section is overly descriptive, listing isotopic values and MRTs without synthesizing them to test core hypotheses. The manuscript should minimize overly detailed, descriptive statistics and focus on synthesizing the major findings in a more concise manner. For example:

Does fracture aperture or infill correlate with water MRT or its proportional contribution to plant xylem water across different seasons? This should be clearly analyzed and presented in the results.

Response: We thank the reviewer for this important comment. We agree that the original Results section was overly descriptive and did not sufficiently synthesize the data to test the core hypotheses of the study. In response, we have substantially revised the Results section to shift the focus from listing isotopic values and MRTs toward a hypothesis-driven synthesis linking fracture physical characteristics to water residence time and plant water uptake. Specifically, we reorganized Sections 3.2 and 3.3 to explicitly examine how fracture aperture and infill conditions relate to (i) fracture water MRT and (ii) the proportional contribution of fracture water to tree xylem water across seasons. Rather than treating fracture aperture as a continuous predictor, we synthesized MRT patterns across fracture types defined by combined aperture size and infill conditions. The revised Results show that variations in MRT cannot be explained by fracture aperture alone. In particular, fractures that are partially or fully filled with soil consistently exhibit longer MRTs and higher seasonal persistence, whereas narrow or relatively open fractures tend to function as fast-draining conduits with short MRTs. This distinction is reflected in seasonal source partitioning, where soil-filled fractures contribute disproportionately to tree water uptake during dry and transitional periods, while open fractures contribute primarily following rainfall events. To support this synthesis, we have reduced repetitive descriptive statistics, reorganized figures to emphasize comparisons among fracture types, and revised the Results text to explicitly link fracture structure, MRT patterns, and seasonal plant water-use strategies. These revisions clarify how fracture aperture and infill jointly regulate water storage and availability in the bedrock, thereby directly addressing the reviewer's concern.

Figure 6 (Source Partitioning): This figure currently presents preliminary data. It should specify the year(s) of data and include uncertainty estimates, such as standard deviations from MixSIAR posteriors. The data should be grouped by hydrological season or fracture density (high vs. low) rather than showing monthly bars for individual sites. This would offer more insights into the data.

Response: We thank the reviewer for this constructive suggestion. We have extensively revised Figure 6 (and added a supplementary Figure D1 in the Appendix) to comprehensively address all raised points. Specifically, regarding the data grouping, instead of presenting data for individual sites or using a simple high/low density classification, we have grouped the data into four distinct fracture micro-habitats defined by both aperture size and infill characteristics, represented as follows: (a) Site A: Medium Open Fractures (aperture 3–10 mm, no infill); (b) Site B: Fully Infilled Fractures (aperture 10–20 mm, fully infilled); (c) Sites C&D: Wide Partially Infilled Fractures (aperture >20 mm, partially infilled); and (d) Site E: Small Open Fractures (aperture <3 mm, no infill). This reclassification offers a more precise mechanistic explanation of how physical structure, particularly the presence of soil infill, regulates water availability. Furthermore, we aggregated the temporal data into 2-month intervals corresponding to six distinct plant phenological stages (Reactivation, Early Growing, Peak Growing, Late Growing, Senescence, and Dormancy) to highlight the critical coupling between physiological demand and hydrological seasonality. We have also explicitly specified the data collection period (April 2024 to March 2025) in the caption and added error bars to all columns, which represent the arithmetic mean of the standard deviations (SD) derived from the MixSIAR posterior distributions, thus providing the requested uncertainty estimates. Finally, to ensure transparency regarding intra-site variability, we have included the new Figure D1 in the Appendix, which displays the seasonal source partitioning results for every individual tree across all sites. Concurrently, we have rewritten the corresponding description in the Results section to highlight the divergent water use strategies driven by these structures. Specifically, demonstrating how trees rooted in soil-filled fractures (Sites B, C, D) maintain stable access to deep water sources during water-limited stages (e.g., Reactivation and Dormancy), whereas those in open fractures (Sites A, E) are constrained to the opportunistic use of recent precipitation.

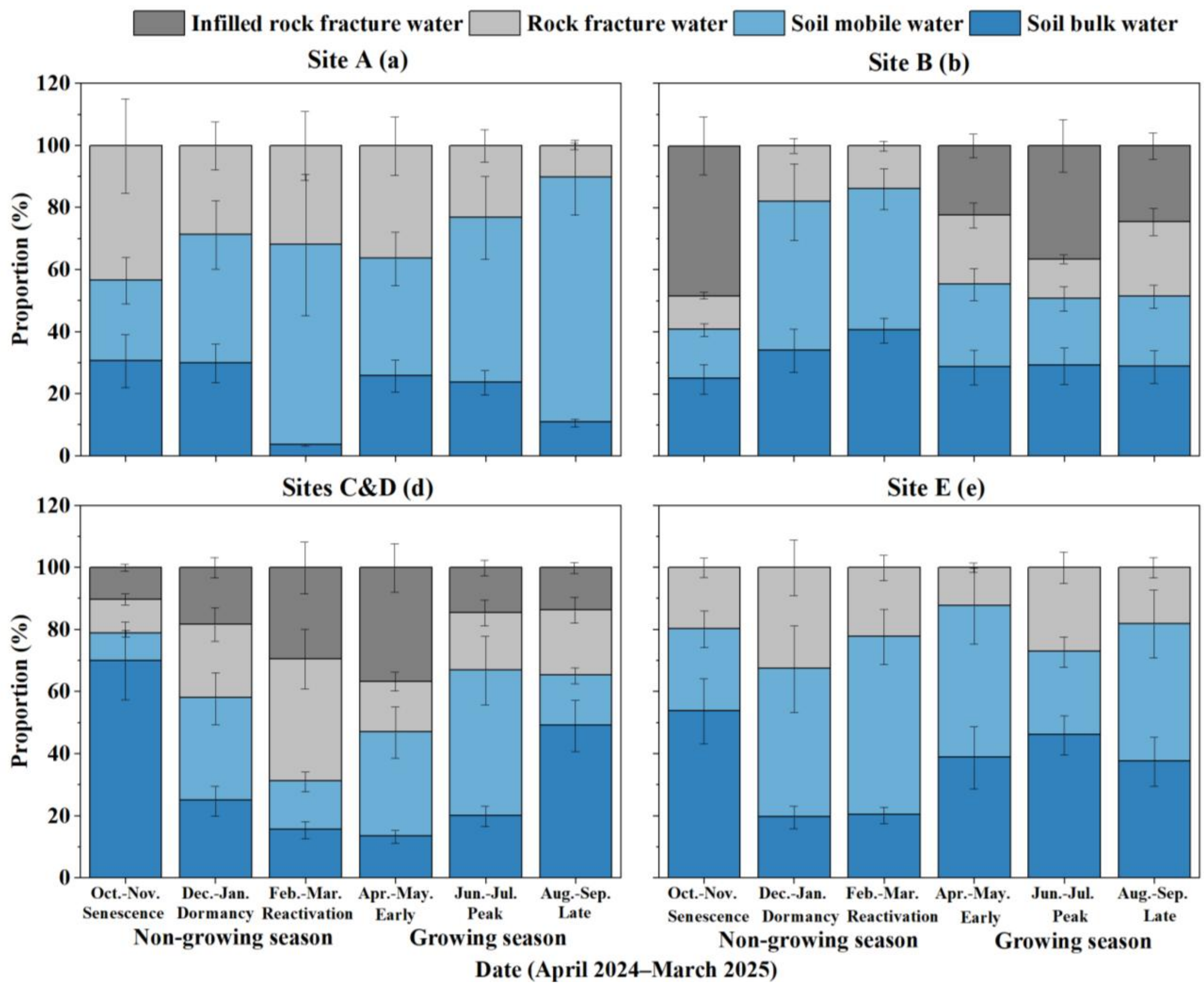


Figure 6. Seasonal variations in the mean proportional contribution of water sources to tree xylem water, grouped by fracture aperture and infill characteristics. Data were collected from April 2024 to March 2025. The panels represent the representative fracture type defining each micro-habitat (noting that while minor fractures are ubiquitous, soil-filled fractures dominate storage at Sites B–D): (a) Site A: medium open fractures (aperture 3–10 mm, no infill); (b) Site B: fully infilled fractures (aperture 10–20 mm, fully infilled); (c) Sites C&D: wide partially infilled fractures (aperture >20 mm, partially infilled); (d) Site E: narrow open fractures (aperture <3 mm, no infill).The X-axis displays data in 2-month intervals corresponding to distinct plant phenological stages (e.g., growing season (early growing, peak growing, late growing), senescence, reactivation, dormancy). Data represent the mean values of all sampled trees within each site group. Error bars indicate ±1 standard deviation (SD) derived from the MixSIAR model outputs.

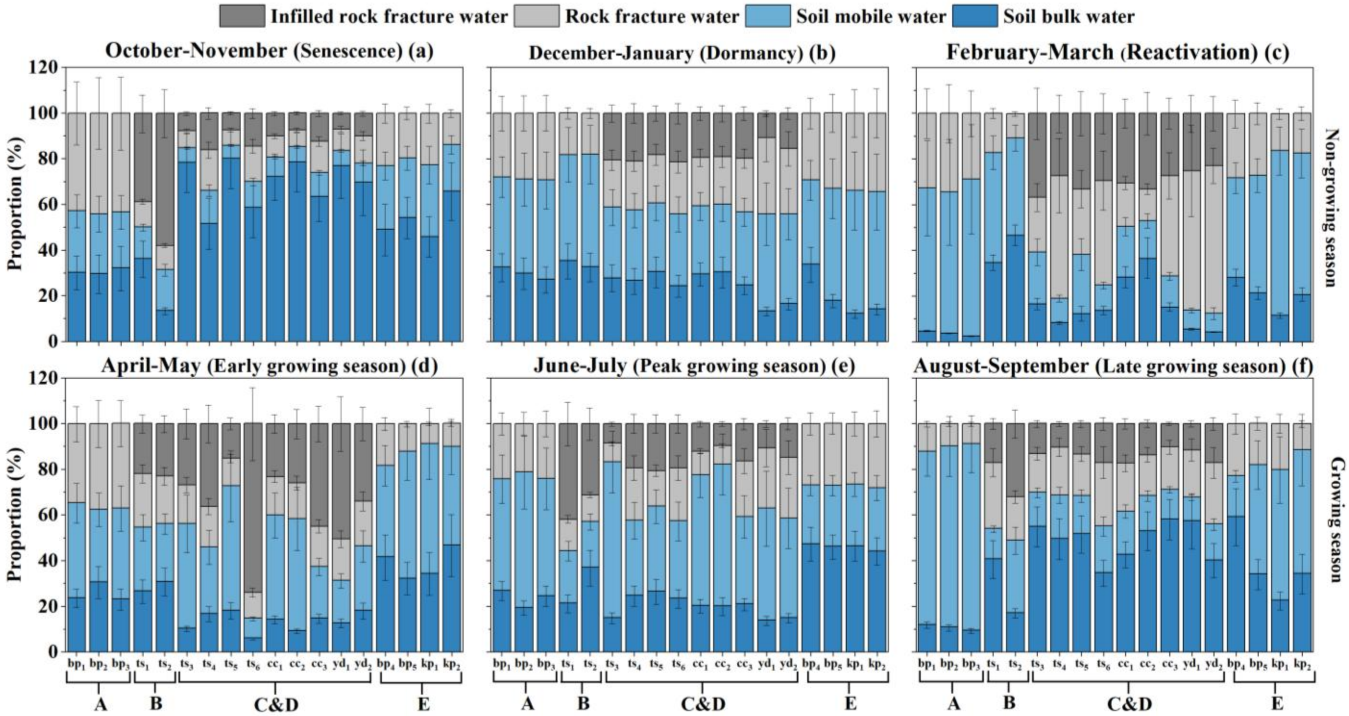


Figure D1. Seasonal variation in the proportional contributions of different water sources to individual tree xylem water across sites. Error bars indicate ±1 standard deviation (SD) derived from the MixSIAR model outputs.

MRT Clarification: In section 3.2, it is unclear whether the reported MRT values are for the same depth or different depths. This should be clarified to ensure the results are presented unambiguously.

Response: We thank the reviewer for this careful observation. We clarify that the reported MRT values represent the arithmetic mean of all successfully collected samples (not a depth-weighted average). It is true that mobile soil water samples could not be collected from the surface layer (0–5 cm) due to the extremely dry conditions and low soil moisture content characteristic of the thin karst soil. However, we argue that this missing fraction has a negligible impact on our conclusion for two reasons: Minimal Contribution to Uptake: In the dry surface layer, the absolute volume of mobile water is extremely low, meaning its contribution to tree water uptake is negligible. Conservative Comparison: Surface mobile water typically has a very short MRT. If it were possible to collect and include these samples, they would only further shorten the average mobile water MRT, thereby increasing the difference between mobile and bulk water (i.e., making our current comparison conservative). To verify this, we compared the mean MRTs excluding the top

5 cm for both pools. The results show that the mobile water MRT (mean 135 days) remains significantly shorter than the bulk soil water MRT (mean 251 days) at the same depth range. Thus, the slight mismatch in sampling depth does not alter the conclusion that mobile water flows significantly faster than the tightly bound bulk water. We have added a clarification in Section 3.2 to address this context.

Revised manuscript text: The MRT of bulk soil water (36-708 days, mean 196 days) was higher than that of mobile soil water (63-459 days, mean 135 days) (Note: Mobile water samples were limited to depths >5 cm due to low moisture content in the surface layer. However, given that surface mobile water typically has a shorter residence time, including these surface samples would likely further reduce the mobile water mean MRT, thereby reinforcing the observed difference between mobile and bulk water pools.).

MRT and MTT Methods: The manuscript calculates both MRT and MTT, but the authors do not explain why both methods are necessary or what the differences between the two are. The values of MRT and MTT differ significantly in some cases, but the manuscript does not provide any explanation of how these differences relate to underlying hydrological processes. Furthermore, the presence of negative MTT values needs to be addressed—why do they occur, and are they physiologically meaningful?

Response: We thank the reviewer for this important comment. We have clarified the conceptual distinction and complementary roles of MTT and MRT in the revised Methods section. Following isotope sine-curve theory, MTT characterizes the phase lag of the seasonal isotope signal between connected water pools and thus reflects the timing of signal propagation, whereas MRT represents the damping-controlled persistence of water within a given pool, integrating storage and internal mixing processes. These two metrics therefore describe different but complementary aspects of water age dynamics and should not be used interchangeably. The observed differences between MTT and MRT arise because signal propagation and water storage are governed by distinct hydrological mechanisms, including preferential flow, piston flow, and internal mixing. In particular, negative MTT values do not imply negative physical travel times. Instead, they indicate that the isotopic signal in the downstream compartment precedes that of the upstream input due to the dominance of older, well-mixed, or deeper water pools. This behavior has been widely reported in isotope-based transit time studies and is physiologically meaningful, reflecting plant uptake of pre-event or long-residence water rather than recent precipitation. In this study, MRT is the primary metric used to interpret water storage and persistence across soil and rock fracture compartments. MTT is calculated and reported in the Supplement to provide complementary information on isotope signal timing and to clearly distinguish transport-related delays from storage-controlled residence times. To avoid over-interpretation, MTT is not further discussed in the main text.

Revised manuscript text: However, beyond mere source attribution, quantifying the temporal dynamics of water movement is essential for characterizing subsurface storage. Metrics such as Mean Residence Time (MRT) and Mean Transit Time (MTT) have been widely employed to estimate catchment water storage durations and the temporal lag between precipitation input and plant uptake (McGuire et al., 2002; Asadollahi et al., 2020; Liu et al., 2024b). While MRT reflects the storage capacity and mixing volume of a reservoir, and MTT characterizes the transport velocity, their application in complex karst environments remains challenging. Unlike homogeneous soils where these methods are effective (Liu et al., 2024b; Stewart and McDonnell, 1991), the high heterogeneity of karst fracture networks creates a dual-domain system characterized by rapid conduit flow and slow matrix storage. This complexity confounds standard residence time estimations (Hartmann et al., 2014; Zhang et al., 2021). Nevertheless, applying MRT and MTT analysis to specific karst water pools (e.g., fracture vs. matrix) offers a unique opportunity to unravel the temporal disparities that drive plant water availability.

Revised manuscript text: To distinguish it from mean residence time (MRT), we applied the mean transit time (MTT) phase shift method from Allen et al. (2018) to quantify the time delay in water transport between compartments. The phase shift captures primarily the time lag between input signals (e.g., precipitation isotopic composition) and output signals (e.g., plant or groundwater isotopic composition). MTT represents the time lag or transmission time between different compartments in the hydrological cycle (e.g., precipitation to soil, soil to rock, rock to plant).

Revised manuscript text: Data in Tables B1–3 show consistently that MRT exceeds MTT. This disparity reflects that the two metrics describe different aspects of water age dynamics within the same compartment. MTT is derived from the phase shift of the seasonal isotope signal and therefore represents the timing of signal propagation between connected compartments. In contrast, MRT is derived from amplitude damping and reflects the persistence of water within a reservoir as controlled by storage volume and internal mixing. Because subsurface storage and mixing can substantially attenuate isotope amplitudes without proportionally delaying signal transmission (due to preferential flow pathways), MRT is typically longer than MTT. Despite this difference in magnitude, the positive relationship between MRT and MTT indicates that subsurface structural properties influence both transport delay and storage persistence.

Table B4 details both the MRT and MTT for different water sources utilized by trees. Here, MRT (derived from amplitude damping) characterizes the mixing volume and turnover time of water within the tree-source system (storage), while MTT (derived from phase shift) quantifies the time lag for water to be transported from the soil/rock source to the tree xylem (uptake delay). Negative MTT values occur when the isotope signal in plant xylem precedes that of water sources. This does not indicate negative physical transport time, but rather reflects the dominance of older or deeper water pools in plant uptake, where isotope signals are seasonally advanced due to prior recharge or long-term storage (Liu et al., 2024b).

5. Discussion

The discussion should place more emphasis on the ecohydrological implications of the study, particularly the role of fracture properties in plant water uptake. The authors should better integrate their findings with existing literature on karst hydrology and ecohydrological separation. There should be more attention paid to how fracture aperture sizes and infill affect water availability and uptake, especially during dry or transitional periods.

Response: We thank the reviewer for this helpful comment. We agree that the discussion should place greater emphasis on the ecohydrological implications of fracture properties for plant water uptake. Accordingly, we have revised Sections 4.1 and 4.3 to more explicitly link fracture aperture and infill conditions to water availability, residence time, and seasonal plant water-use patterns. In the revised discussion, we show that fracture aperture size and soil infill strongly influence water MRT and therefore control whether fractures primarily act as fast flow pathways or as longer-term water storage. Large, soil-filled fractures (>10–20 mm) exhibit substantially longer MRTs (up to

303 days), indicating slowly renewed water pools that can maintain water availability across dry and transitional periods. This provides a mechanistic explanation for the high contribution of fracture water observed at fracture-rich sites and in large, deep-rooted trees (e.g., ts_6), particularly when shallow soil water is limited. We further clarify that different fracture types play contrasting ecohydrological roles. Open or narrow fractures mainly facilitate rapid recharge and short-term uptake following rainfall, whereas soil-filled fractures retain water for longer periods and support transpiration during dry seasons and phenological transitions, such as late winter reactivation and early growing season. We therefore expanded the discussion of these transitional periods, highlighting their importance for understanding fracture-mediated plant water use. Finally, we more closely integrate our findings with previous studies on karst hydrology, bedrock water storage, and ecohydrological separation. Our results suggest that, in karst systems, ecohydrological separation is not solely a soil-based phenomenon but is strongly influenced by fracture-controlled storage and connectivity. Separation is most pronounced under dry conditions and becomes weaker during wet periods when hydraulic connectivity increases. These revisions strengthen the ecohydrological interpretation of our results and clarify the role of fracture heterogeneity in regulating plant water uptake and ecosystem functioning in karst landscapes.

6. Study Design Limitations and Confounding Factors

Site and Species Confounding: The study involves different tree species at each site. It is possible that differences in water sourcing patterns could be driven by species-specific rooting strategies rather than fracture characteristics. This potential confounding factor should be addressed more clearly.

Response: We thank the reviewer for raising this important point regarding potential species-specific confounding effects. We acknowledge that tree species composition varies across the study sites, which could in principle influence plant water uptake strategies through differences in rooting depth or physiology. However, based on both the design of the present study and independent evidence from our previous work (Liu et al., 2025), we clarify that habitat structure, specifically soil–fracture configuration, rather than species identity, exerts the primary control on water uptake strategies in this karst ecosystem. In Liu et al. (2025), we explicitly disentangled the effects of species identity and subsurface structure by comparing (i) the same tree species growing under contrasting soil–rock configurations and (ii) different tree species growing within similar soil–fracture settings. That analysis showed that trees occupying similar soil and fracture environments exhibited comparable water sourcing patterns regardless of species, whereas the same species displayed markedly different water-use strategies when growing under different soil–rock structures. These results demonstrate that fracture properties and soil-rock architecture dominate plant water-use behavior in karst landscapes. The present study builds on this foundation by focusing on fracture characteristics as the primary explanatory variable. The consistency of water-use patterns within similar fracture settings, together with the divergence observed across sites with contrasting fracture aperture and infill conditions, supports our interpretation that the observed differences are driven by subsurface structure rather than species-specific traits. We have clarified this point in the revised manuscript by explicitly acknowledging this potential confounding factor and by referencing the conclusions of Liu et al. (2025).

Pseudoreplication: The study design lacks true replication of fracture types across sites, which limits the ability to generalize findings about the role of fractures in plant water uptake. This limitation should be acknowledged and discussed.

Response: We thank the reviewer for raising the issue of potential pseudoreplication. We acknowledge that the study does not provide strict landscape-level replication, in the sense of multiple independent sites for each fracture type. This limitation is now explicitly acknowledged in the revised manuscript, and the scope of inference has been clarified as process-based rather than intended for broad statistical generalization. The fracture types investigated here were defined based on an intensive structural survey conducted at the same five representative sites. In our prior work (Liu et al., 2024a) 260 individual fractures and 38 rock boreholes (Figure R1) were systematically characterized across these sites in terms of aperture size, depth, and degree of soil infill. This dataset provided the empirical basis for fracture classification and for selecting the sites investigated in the present study, ensuring that they represent dominant fracture end-members within this karst setting. Importantly, the effective replication in this study occurs at the process level rather than solely at the site level. A key methodological feature is the direct sampling of water from individual fractures, which allows fracture-specific residence times and isotopic signatures to be resolved, rather than relying on mixed epikarst or bulk bedrock water. This fracture-scale sampling substantially increases mechanistic resolution and enables direct linkage between fracture properties and plant water uptake. In addition, biological replication was incorporated by sampling multiple individual trees within each site (n = 3–6). The consistency of isotopic patterns among trees sharing similar soil–fracture configurations indicates that the observed water-use strategies are primarily controlled by fracture structure rather than random site effects. We therefore frame this study as a process-oriented analysis that elucidates how fracture properties regulate water storage and plant water uptake in karst systems. This framing, together with the acknowledged limitation regarding site replication and the need for broader spatial replication in future studies, has been explicitly incorporated into the revised Discussion (Section 4.3).

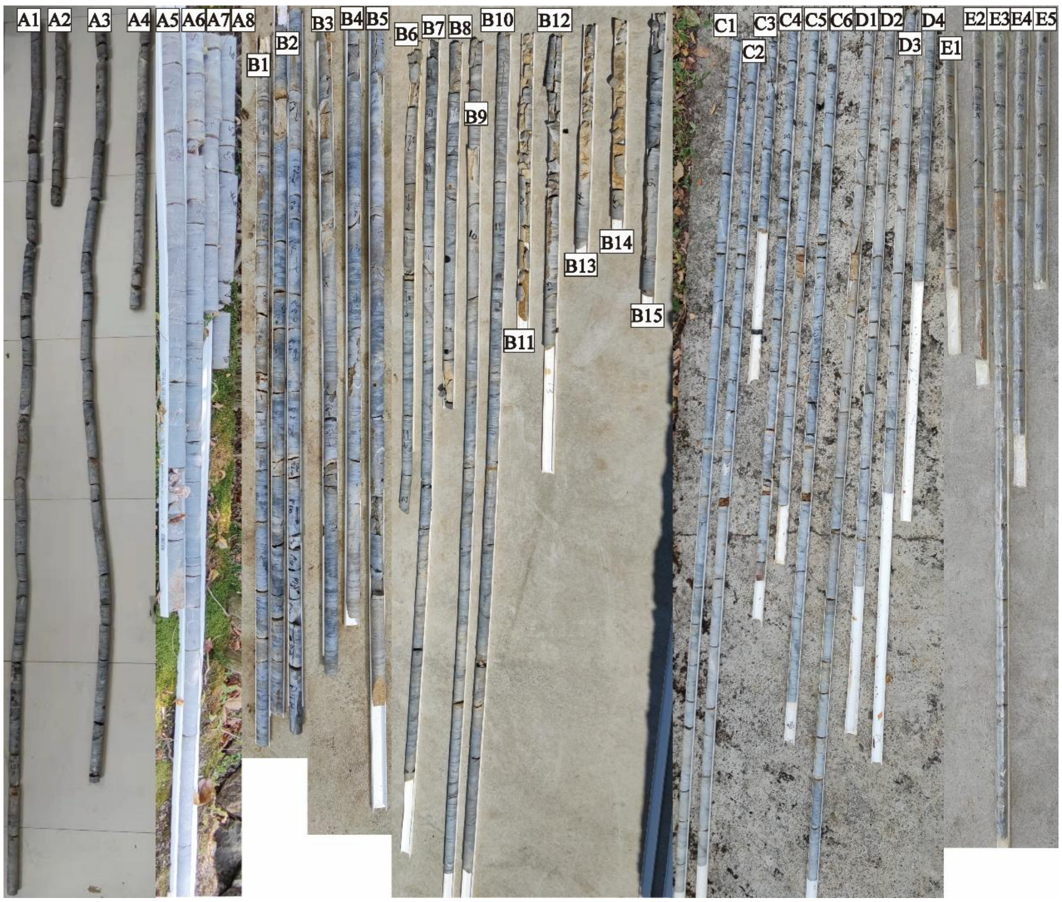


Figure R1. Borehole core samples

Representativeness: The conclusions are drawn from a single study site. Given the extreme heterogeneity of karst landscapes, the authors should frame their findings as a case study rather than assuming general applicability to all karst environments.

Response: We thank the reviewer for this important caution. We agree that, given the extreme structural and hydrological heterogeneity of karst landscapes, the conclusions of this study should be framed primarily as a mechanistic case study, rather than as a model intended to be universally applicable to all karst environments. Accordingly, we have revised the Abstract, Discussion, and Conclusions to explicitly limit broad generalization and to clarify the scope of inference. At the same time, we clarify the context in which our findings remain informative beyond this single site. Previous work conducted at the same study location (Liu et al., 2024a) has shown that the hydraulic behavior of open fractures follows established physical principles, such as cubic-law scaling between fracture aperture and hydraulic conductivity, while systematic deviations arise when fractures are partially or fully filled with soil. This indicates that although absolute values of hydraulic parameters and residence times are site-specific, the mechanistic role of fracture aperture and infill in regulating water transmission and retention is a fundamental property of fractured limestone systems, rather than an anomaly unique to this site. More broadly, the ecohydrological relevance of fractured bedrock as a plant water source is not restricted to karst terrains. Similar controls of rock habitat structure on vegetation water use have been reported in other shallow-soil, fractured-rock ecosystems. In this sense, our study does not claim direct transferability of quantitative results (e.g., MRT values) to all karst systems. Instead, it provides a process-based framework for understanding how structural heterogeneity in bedrock governs water storage, availability, and plant uptake. In addition, the fracture-scale sampling approach developed here, which targets water from individual fractures rather than mixed epikarst or bedrock reservoirs, offers a methodological reference that can be applied and tested in other heterogeneous geological settings. We have therefore revised the Discussion to emphasize that our conclusions are intended to (i) elucidate process-level controls linking fracture properties to ecohydrological function, and (ii) motivate future studies to evaluate the broader applicability of these mechanisms across different lithologies and climatic regimes.

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